



LCLS-II Cryomodule Design

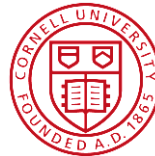
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LCWS14

7 Oct 2014



NATIONAL
ACCELERATOR
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Fermilab

Jefferson Lab



Outline

Linac and cryogenic system configuration

Cryomodule configuration

Cryomodule design

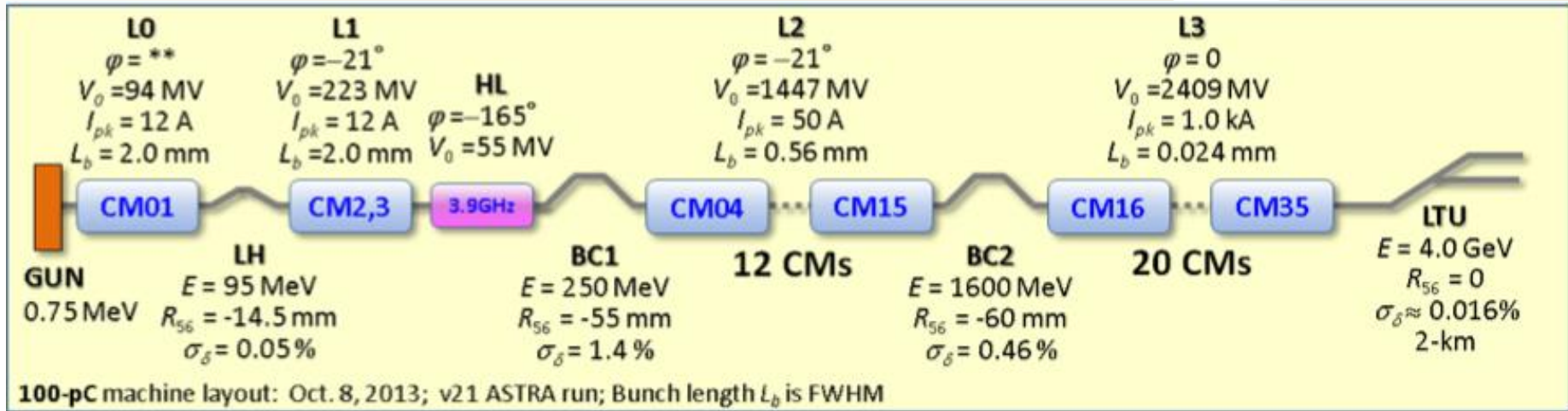
Heat loads

Cryomodule and system thermal and fluid dynamic design

Conclusions

Additional information

LCLS-II Linac



- Thirty-five **1.3 GHz 8-cavity cryomodules**
- Two **3.9 GHz 8-cavity cryomodules**
- Four cold segments (L0, L1, L2 and L3) which are separated by warm beamline sections.

Physics Requirements Document: “SCRF 1.3 GHz Cryomodule,”
LCLSII-4.1-PR-0146-R0, 4/30/2014 Original Release.
Physics Requirements Document: “SCRF 3.9 GHz Cryomodule,”
LCLSII-4.1-PR-0097-R0, 6/23/2014 Original Release.

Parameters for the Accelerator

Table 1. LCLS-II Electron Beam Parameters

Parameter	Nominal	Range	Units
Final electron energy	4	2-4.14	GeV
Electron bunch charge	0.1	0.01-0.3	nC
Bunch repetition rate	0.62	0-0.93	MHz
Average linac current	62	1-300	μA
Average beam power	0.25	≤1.2	MW
emittance	0.45	0.2-0.7	μm
Peak current	1	0.5-1.5	kA
Bunch length	8.3	0.6-52	μm
Usable bunch length	50		%
Compression factor	85	25-150	
Slice energy spread	0.5	0.15-1.5	MeV
Beam stability goals			
Energy, rms	<0.01		%
Peak Current	<5		%
Bunch arrival time	<20		fs
beam stability (x, y)	<10		%

From John Galayda,
DOE review,
1 Oct 2014

LCLS-II cryomodules: top level parameters

Cryomodule (CM) Parameters	Symbol	nom.value	Units
Cavity operating temperature	T_{cryo}	2	K
# 9-cell cavities per cryomodule (1.3 GHz)	N_{cav}	8	-
# installed cryomodules (1.3 GHz)	N_{CM}	35	-
# 3.9-GHz cavities per 3.9 GHz CM	-	8	-
# 3.9 installed GHz cryomodules	-	2	-
# installed 1.3 GHz cryomodules in L0	N_{CM0}	1	-
# installed 1.3 GHz cryomodules in L1	N_{CM1}	2	-
# installed 3.9-GHz cryomodules as linearizer	N_{CMLH}	2	-
# installed cryomodules in L2	N_{CM2}	12	-
# installed cryomodules in L3	N_{CM3}	20	-

Cryomodule Cavity Requirements (LCLSII-4.1-PR-0146)

... cavities will be capable of operating at **16 MV/m CW** with a **$Q_0 = 2.7e10$** at 2K....

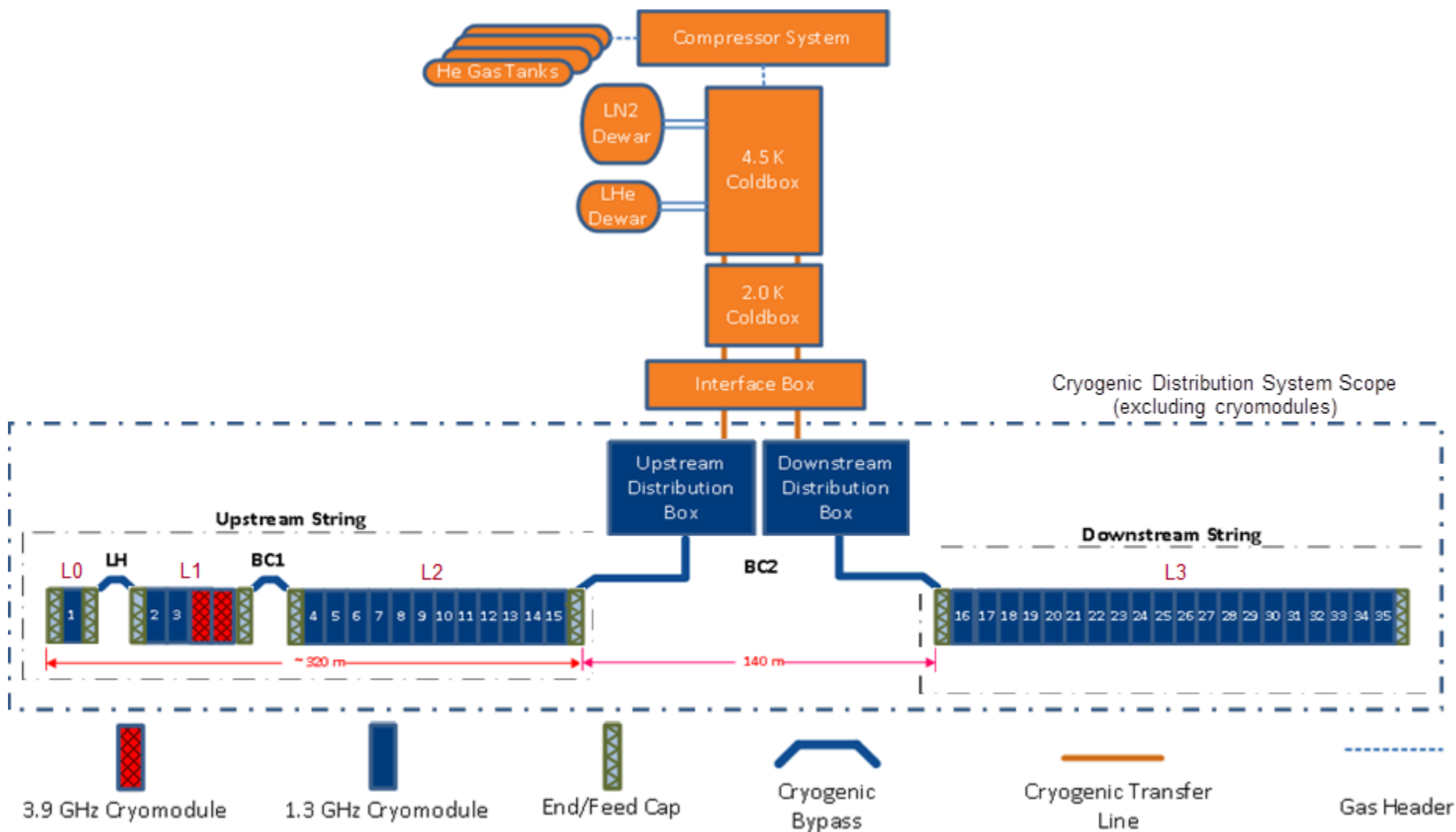
From Marc Ross,
DOE review,
1 Oct 2014

- average of $1/Q_0 < 1 / 2.7e10$
- matches anticipated cryoplant heat-load capacity
- (the acceptable variation of Q_0 is large \rightarrow min $Q_0 > 1.5e10$)

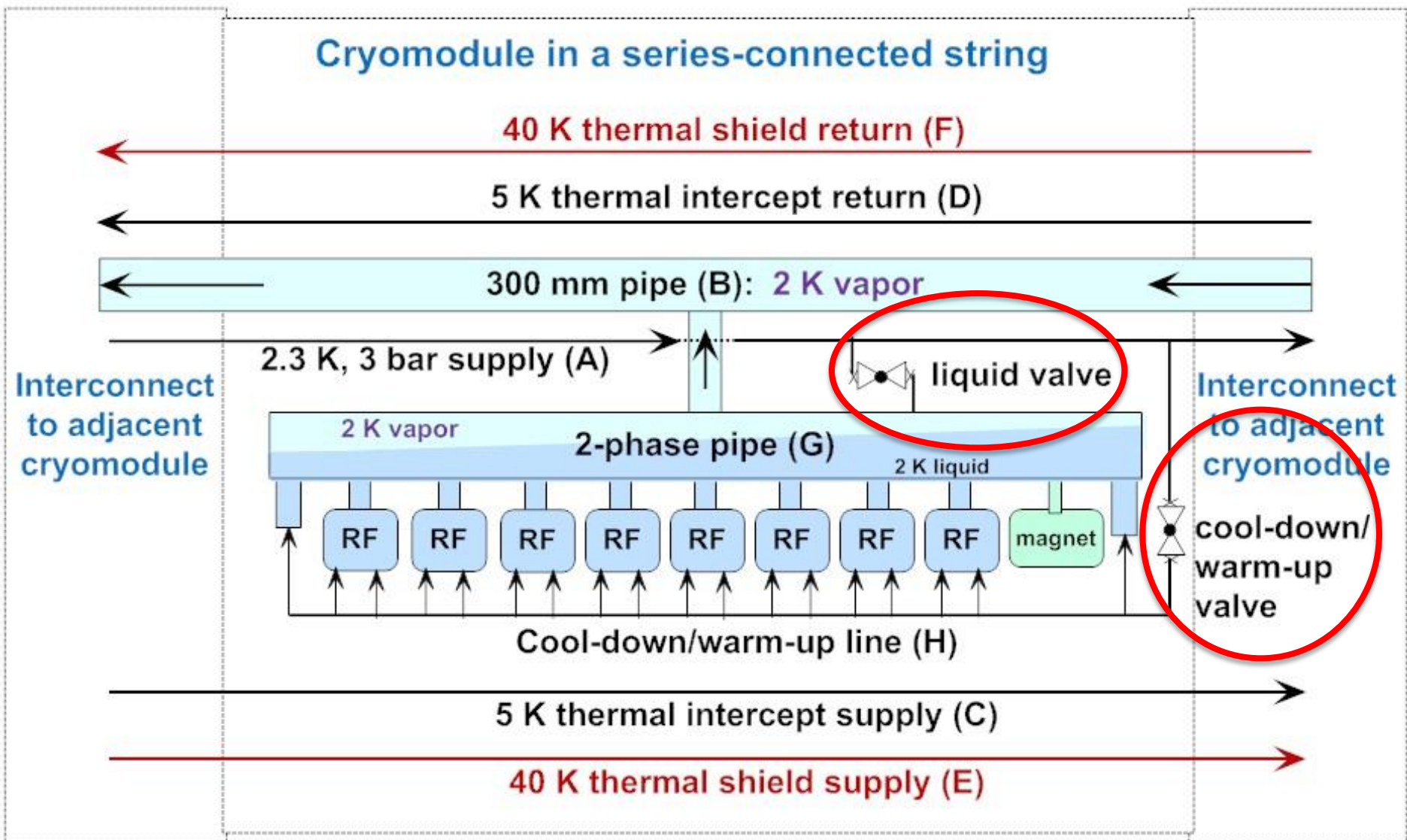
The individual cavities will be qualified to operate up to a **voltage of at least 18 MV/m CW**

- 15% 'degradation' margin Cryomodule / Vertical Test (CM/VT) included
- (10% reported by DESY first 7 XFEL CM – Linac 2014)

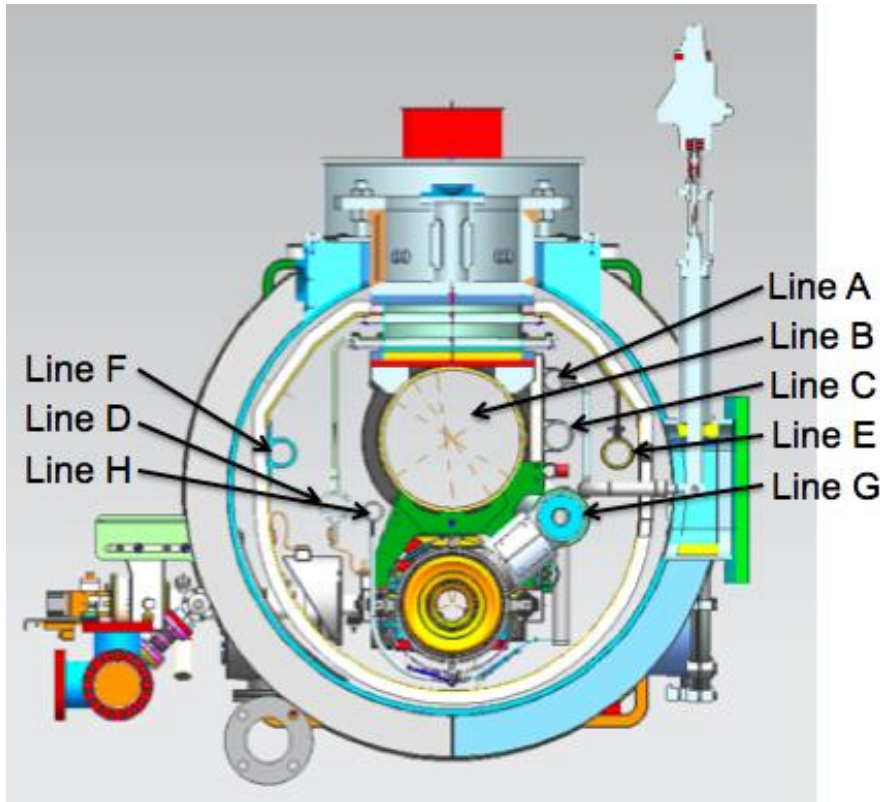
The Cryogenic System



Modifications for individual liquid level control at each cryomodule and for fast cool-down



LCLS-II Cryomodule (CM) Cryogenic Circuits

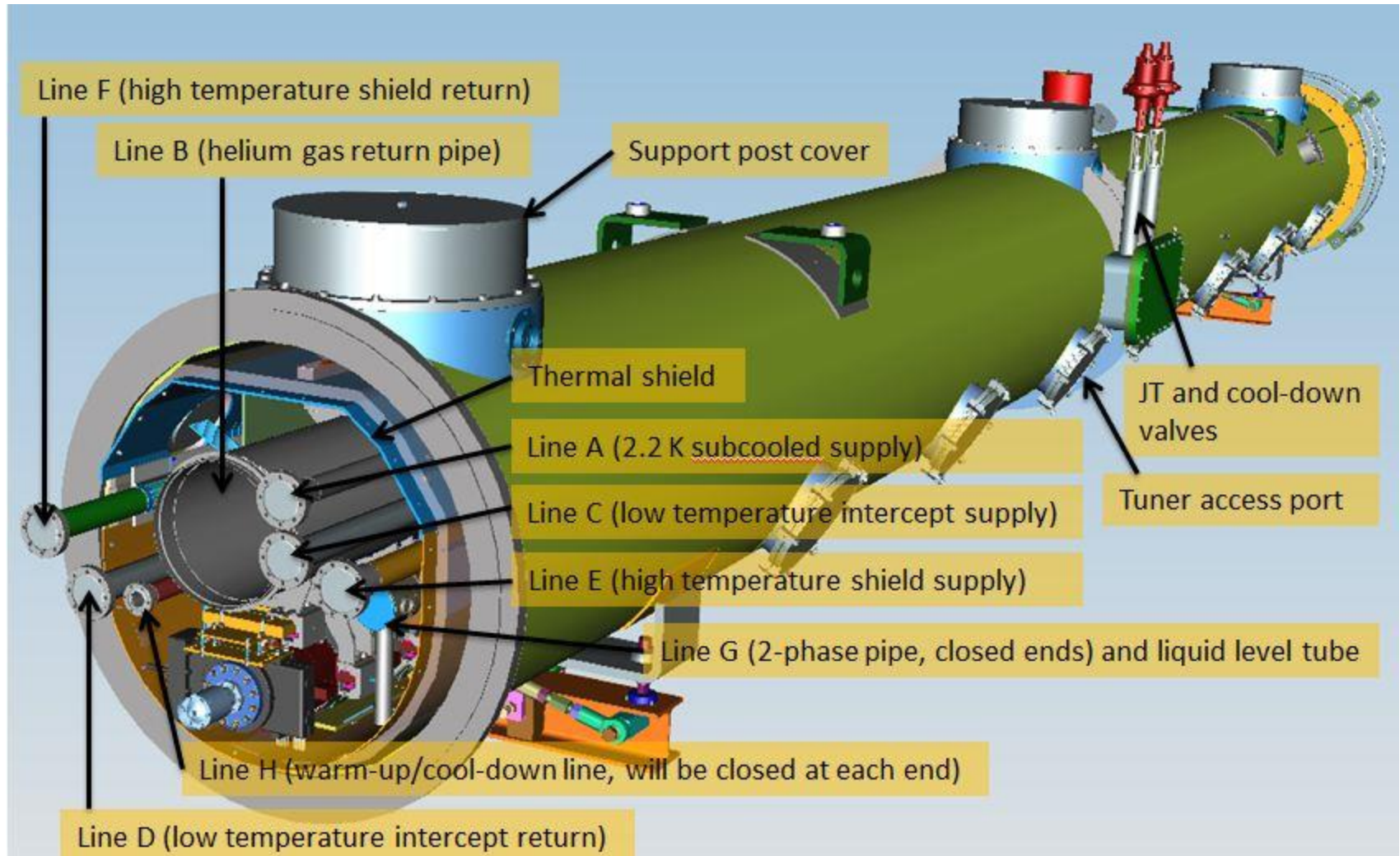


Circuit (Line)

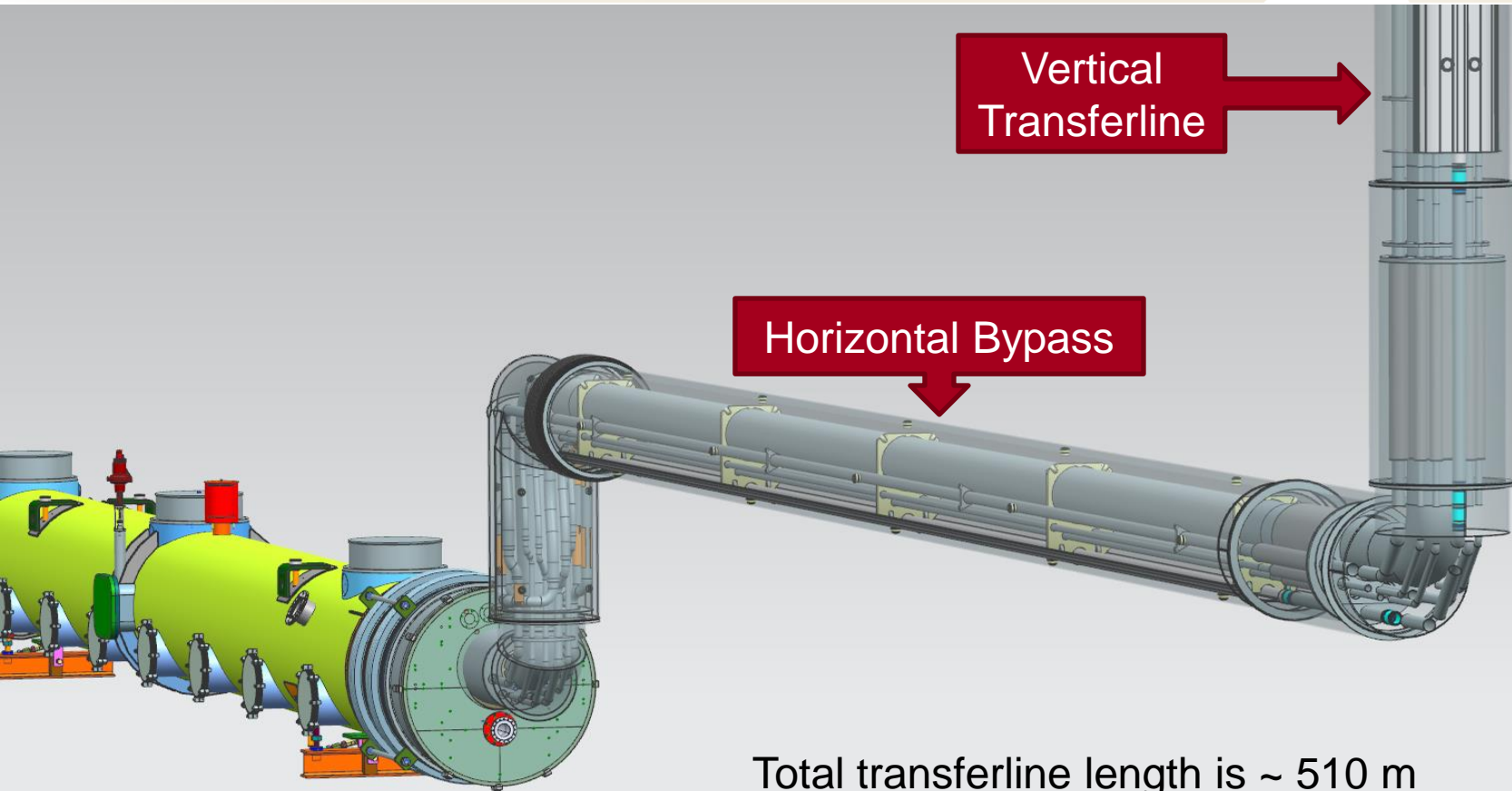
- A. 2.2 K subcooled supply
- B. Gas return pipe (GRP)
- C. Low temperature intercept supply
- D. Low temperature intercept return
- E. High temperature shield supply
- F. High temperature shield return
- G. 2-phase pipe
- H. Warm-up/cool-down line

Operating Parameters	A	B	C	D	E	F	G	H
Pressure, [bar]	3	0.031	3	2.8	3.7	2.7	0.031	3
Temperature, K	2.4	2.0	4.5	5.5	35	55	2.0	2.0

Cryomodule image from 3-D model



CM, Feed Cap and Bypass and Vertical Transferline



ILC Type 3+ CM Modifications for LCLS-II (components)

Component design – leverage existing designs

- Cavities – XFEL identical
- Helium vessel – XFEL-like
- HOM coupler – XFEL-like or –identical
- Magnetic shielding – increased from XFEL/ILC to maintain high Q0
- Tuner – XFEL-like end-lever style
- Magnet – Fermilab/KEK design split quadrupole
- BPM – DESY button-style with modified feedthrough
- Coupler – XFEL-like (TTF3) modified for higher QL and 7 kW CW

Concerns based on global experience

- Tuner motor and piezo lifetime: adding access ports
- Maintain high Q0 by minimizing flux trapping: new constraints on cool-down rate through transition temperature

Functional Requirements Document: “1.3 GHz Superconducting RF Cryomodule,” LCLSII-4.5-FR-0053-R0, 6/23/2014 Original Release.

ILC Type 3+ CM Modifications for LCLS-II (cryo-mech)

Cryo-mechanical design – increased pipe sizes

- Larger chimney pipe from helium vessel to 2-phase pipe
- Larger 2-phase pipe (~100 mm OD) for low velocity vapor flow

Both high heat load & 0.5% slope of the SLAC tunnel require

- Closed-ended 2-phase pipe (line G) providing separate 2 K liquid levels in each cryomodule
- 2 K JT (liquid supply) valve on each cryomodule

For fast cool-down, cool one cryomodule at a time

- Closed-ended warm-up/cool-down manifold (line H)
- Cool-down/warm-up valve on each cryomodule

Cost savings: Omit 5 K thermal shield

- Simplification since large dynamic heat at 2 K makes such a thermal shield of marginal value
- Retain 5 K intercepts on input coupler

Q0 preservation imposes some new requirements

High Q0 is required

- We assume $Q_0 = 2.7E10$ in our design

Magnetic shielding to keep < 5 mGauss

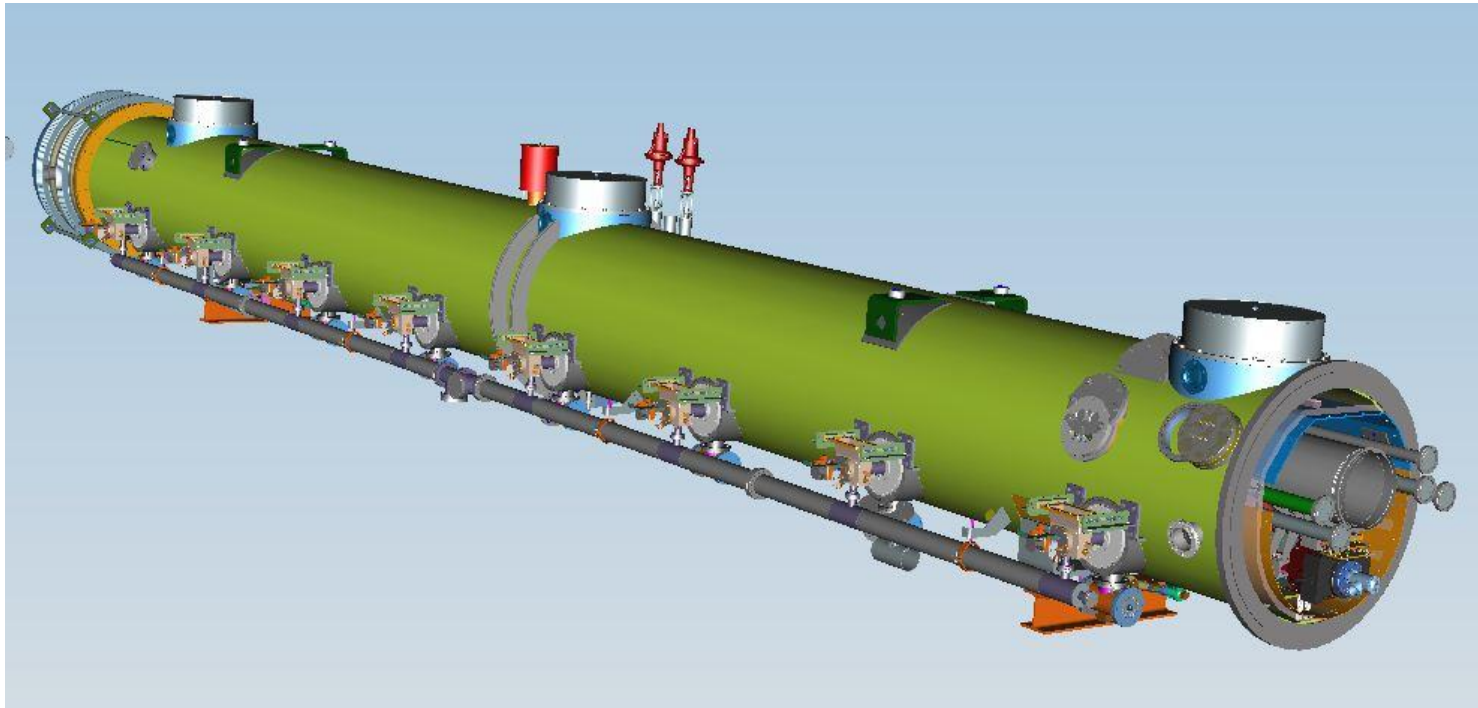
- New features such as active external coils

Cool-down rate

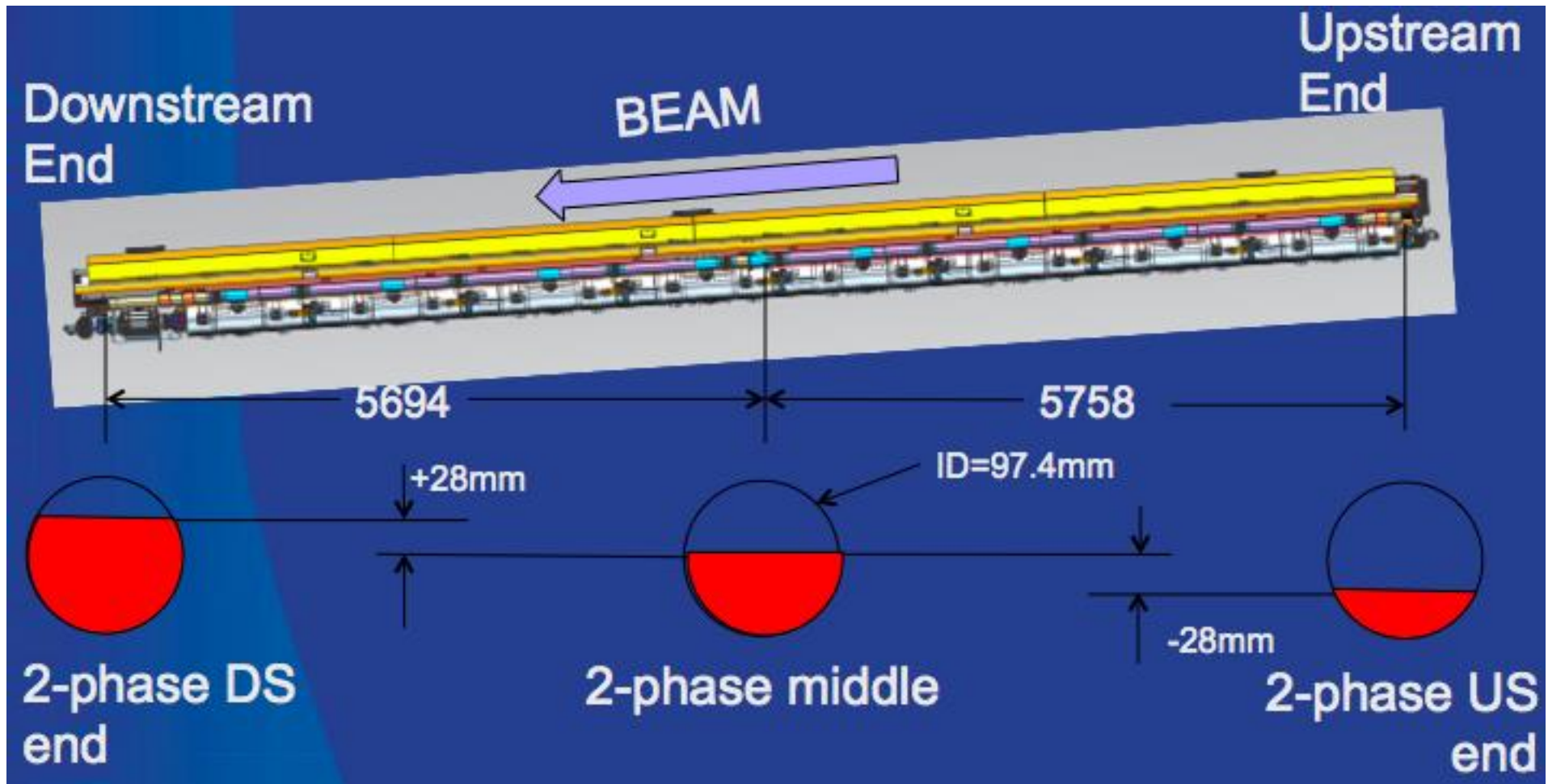
- High rate of cool-down appears to be necessary
- As much as 2 – 3 Kelvin/minute through 9.2 K transition temperature
- Key may be high ΔT within Nb to “sweep out” magnetic flux
- We have some concepts for fast cooling
- Uniform cooling of bimetallic joints

1.3 GHz LCLS-II Cryomodule

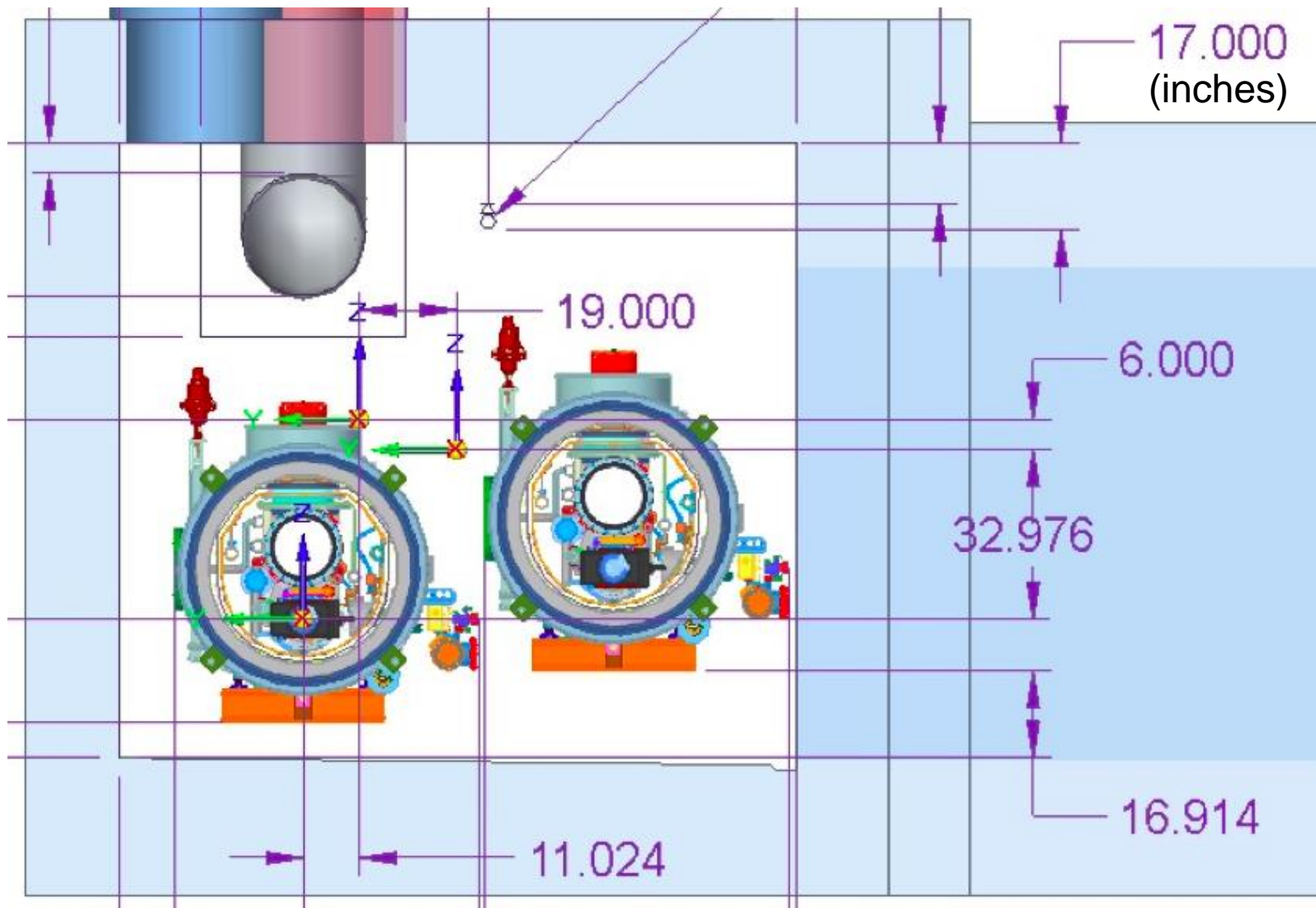
- Vacuum vessel
- Interconnection Bellows
- Power coupler warm parts
- Cryomodule alignment supports
- Cryomodule instrumentation ports
- Power coupler pumping line



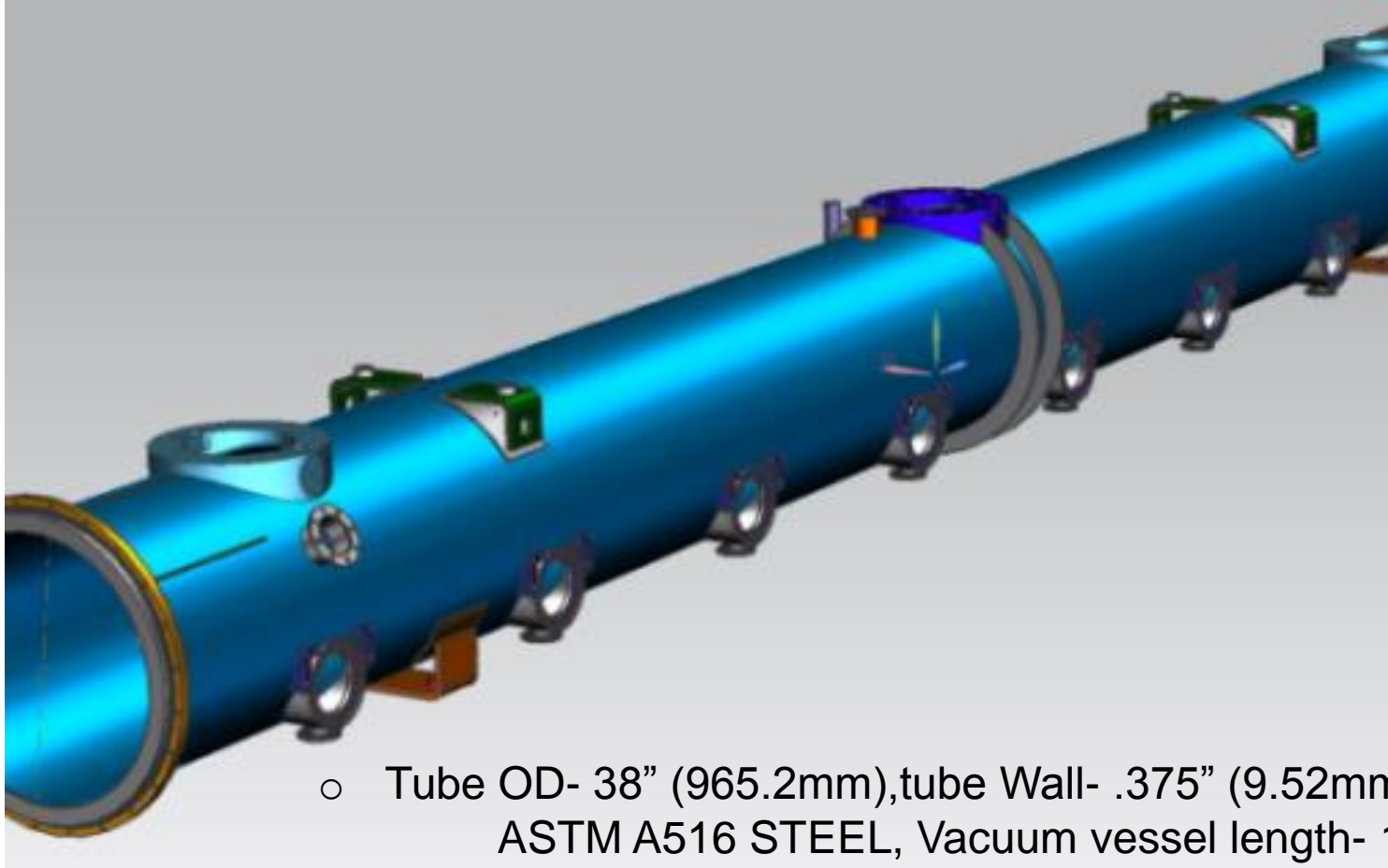
1.3 GHz CM in LCLS-II SLAC Tunnel with Slope $\sim 0.5\%$



SLAC tunnel (~ 3 meters x 3 meters) results in extremely limited space

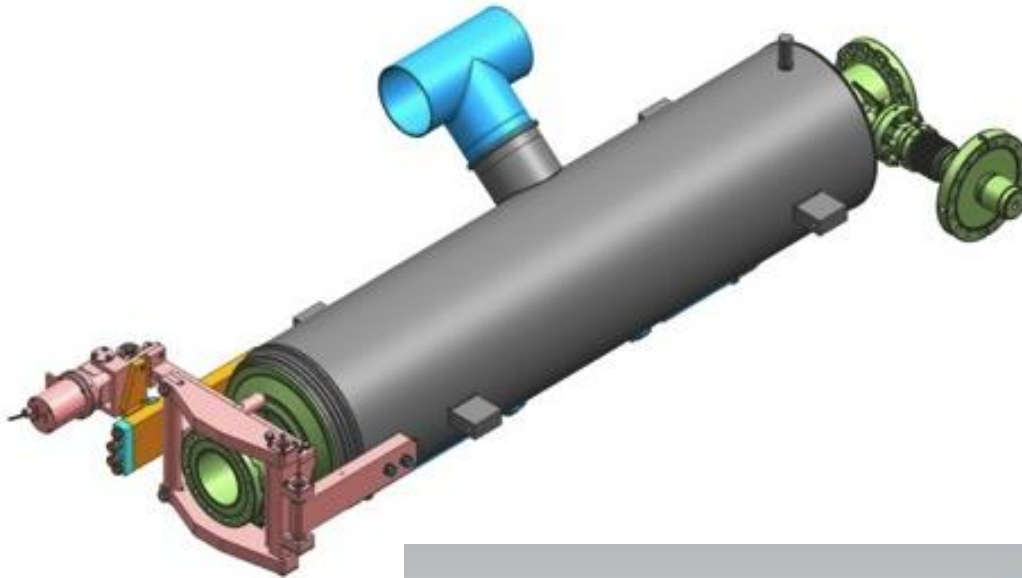


LCLS-II 1.3 GHz Cryomodule Vacuum Vessel

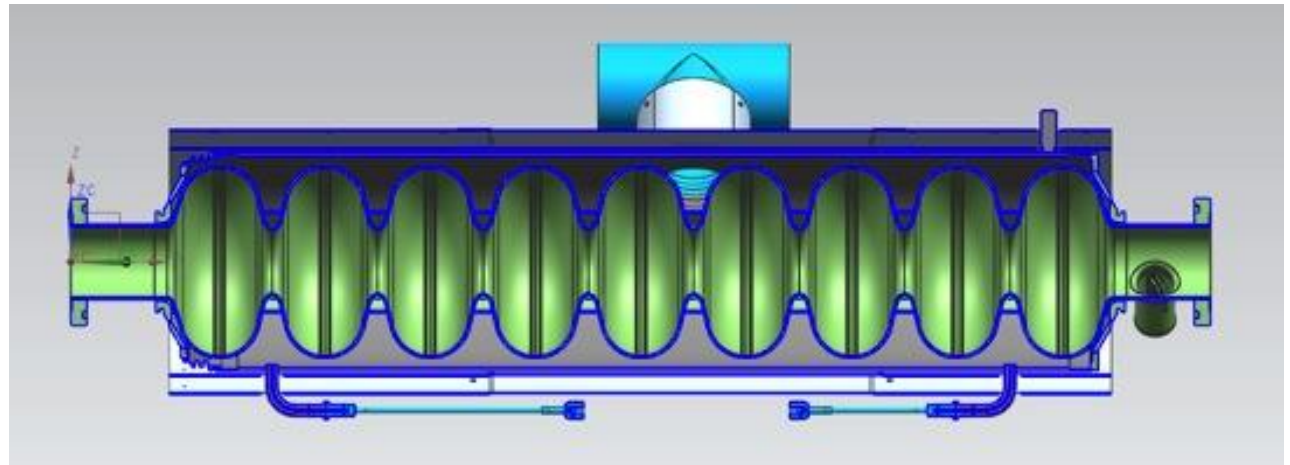


- Tube OD- 38" (965.2mm), tube Wall- .375" (9.52mm), ASTM A516 STEEL, Vacuum vessel length- 11400mm
- Final machining: MC port and cold mass SLD support surfaces
- A critical component for Q0 preservation, must be demagnetized

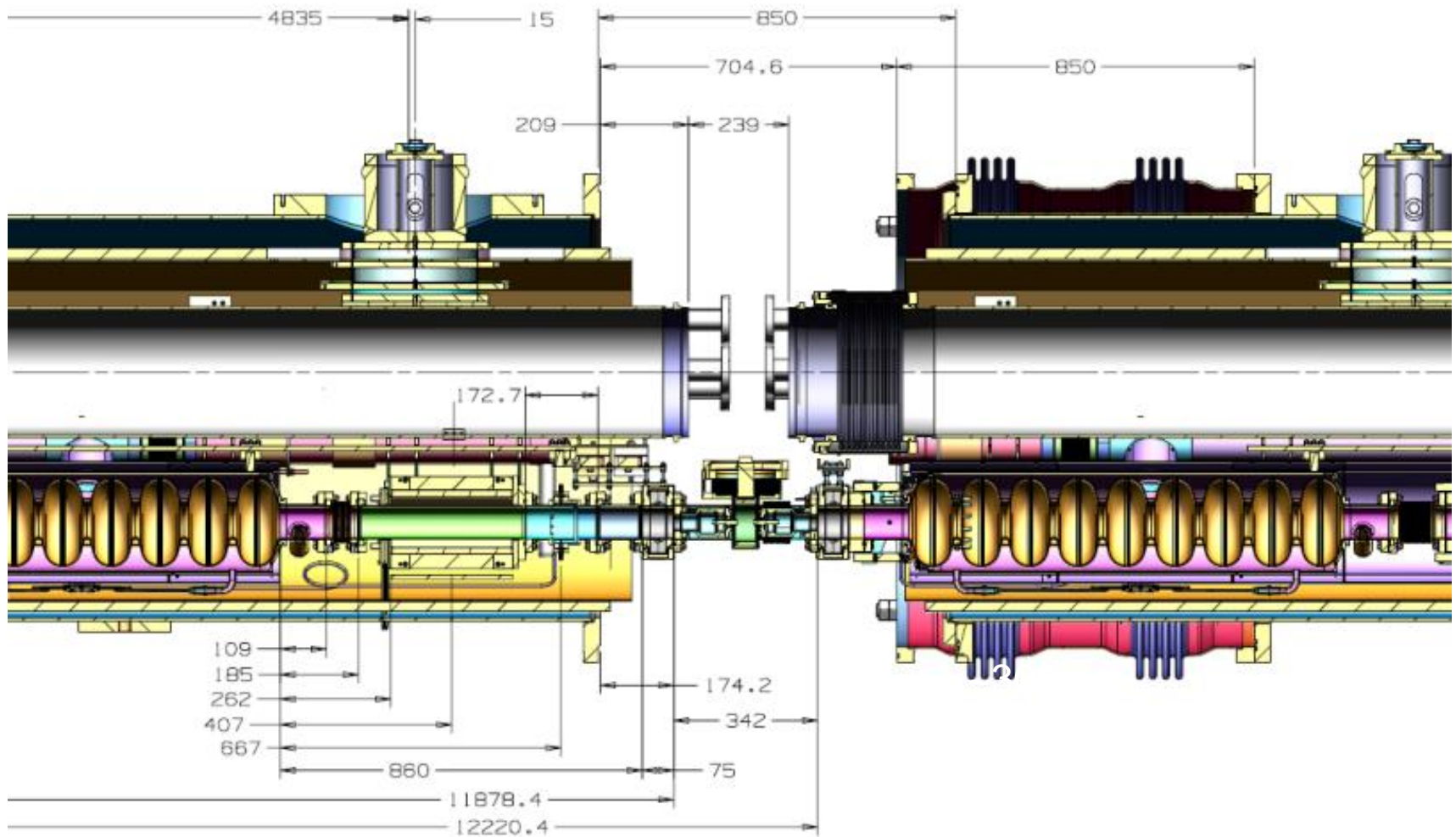
LCLS-II dressed cavity



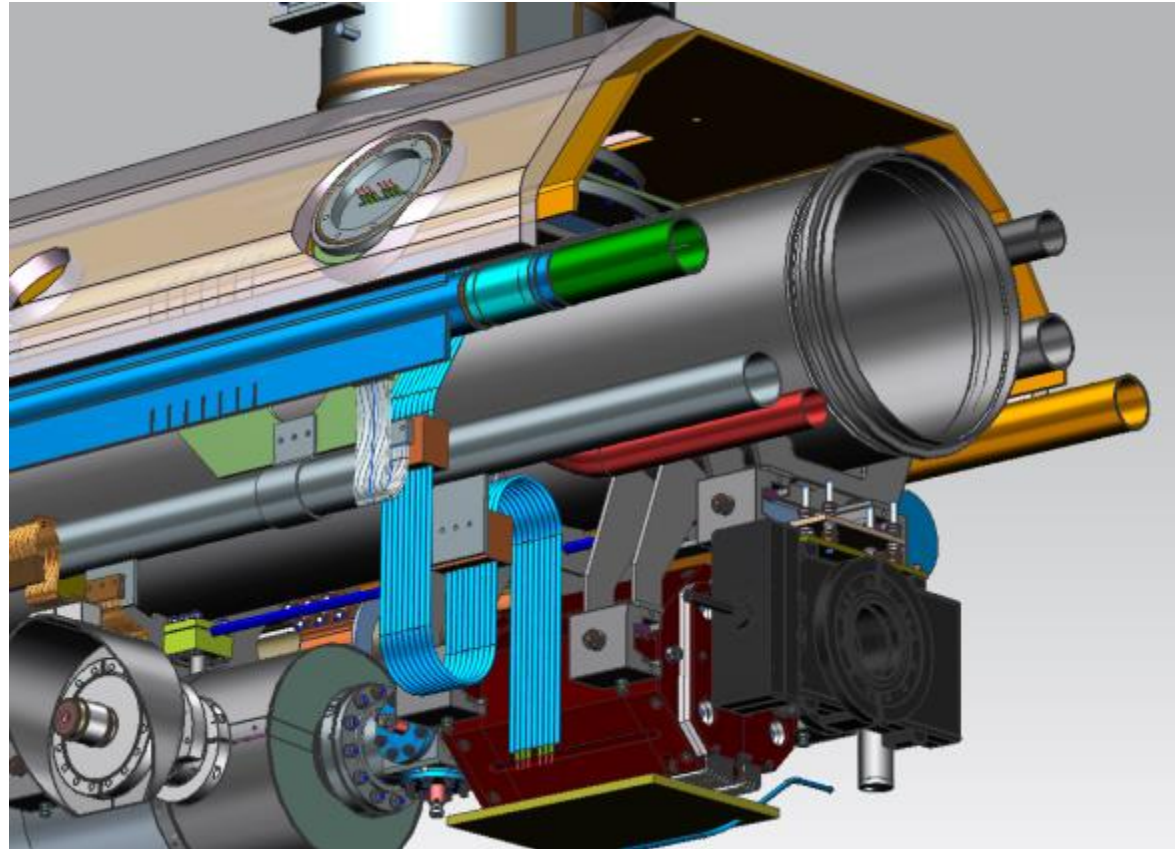
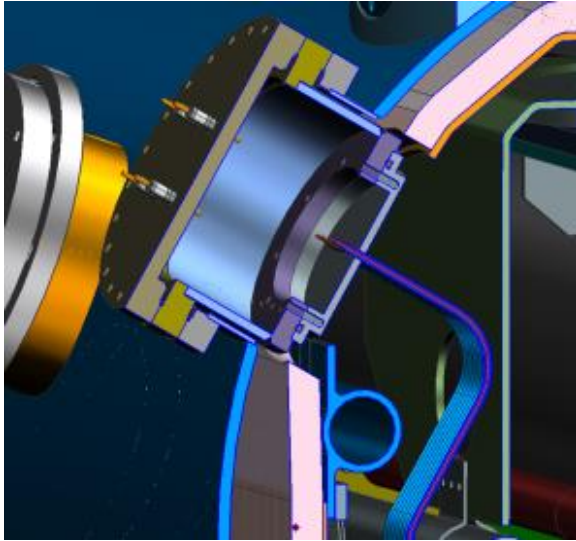
- Dual inlet ports
- Explosion-bonded Ti-SS transition on 2-phase nozzle. Stainless 2-phase pipes and bellows.
- End lever tuner with integrated piezos



LCLS-II, 1.3 GHz Cryomodules connection



1.3GHz CM. Current Leads & Splittable Quad Magnet



Conduction cooled

intercept to 2-phase He pipe for Quadrupole

CL-SSR1 Style, 50A, quantity-6 (+2 tubes for instrumentation),

2-thermal intercepts (5K & 50K)

BPM between magnet and last cavity – moves magnet further from cavity

1.3 GHz (and 3.9 GHz) CM Thermal and Hydraulic Design

LCLS-II CM is a modified TESLA/XFEL CM for CW mode operation

- Thermal shields, intercept flow, and cryogenic supply and return flow in series through a string of cryomodules

Heat load range

- 80 to 150 W per cryomodule at 2 K depending on local HOM deposition and cavity Q0
- A cavity may see as much as 25 W
- Dynamic heating at 2.0 K is about 92% of the 2.0 K cryomodule heat and about 78% of the total cryogenic cooling requirement

Two-phase pipe is 100 mm diameter

- 0.5% slope or 6 cm elevation difference over 12 m
- 100 mm diameter two-phase pipe is nearly full at one end, nearly empty at the opposite end

Cryomodule (CM) thermal and hydraulic design is well advanced

- Steady-state flows and upset conditions with venting analyses
- Incorporating features for faster cool-down (high dT/dx on the cavity)

Cryogenic System Heat Load Sources

Static

- Supports (conduction)
- Thermal radiation
- Magnet current leads
- Input coupler
- Cryogenic distribution system (CDS)

Dynamic

- RF load
- Magnet current leads
- Electrical heaters
- Input coupler
- HOM coupler cables
- HOM and wakefield heating
- Other sources (dark current, tube bellows, etc)

Document that summarizes heat loads estimate that were received from various experts on their respective elements or subsystems - **LCLS-II Cryogenic Heat Load , Note Number: LCLSII-4.5-EN-0179**

Best estimate of linac heat loads (no uncertainty factors included)

Predicted Heat Loads (base, no margin)	High Temperature Thermal Shield	Low Temperature Thermal Intercepts	2.0 K level
Upstream Static heat, [kW]	4.05	0.39	0.25
Downstream Static heat, [kW]	3.00	0.32	0.18
Upstream Dynamic heat, [kW]	1.04	0.05	1.23
Downstream Dynamic heat, [kW]	1.34	0.10	1.47
Total Upstream heat, [kW]	5.09	0.44	1.49
Total Downstream heat, [kW]	4.35	0.42	1.66
Total heat for LCLS-II linac, [kW]	9.44	0.86	3.14

From: SLAC Engineering Note: LCLS-II Cryogenic Heat Load
Note Number: LCLSII-4.5-EN-0179
About 80 W per cryomodule at 2.0 K

Linac design heat loads (uncertainty factors included)

Maximum Expected Heat Loads (with uncertainty factor)	High Temperature Thermal Shield	Low Temperature Thermal Intercepts	2.0 K level
Upstream Static heat, [kW]	5.27	0.50	0.33
Downstream Static heat, [kW]	3.91	0.41	0.24
Upstream Dynamic heat, [kW]	1.14	0.06	1.36
Downstream Dynamic heat, [kW]	1.48	0.11	1.62
Total Upstream heat, [kW]	6.41	0.56	1.69
Total Downstream heat, [kW]	5.38	0.52	1.86
Total heat for LCLS-II linac, [kW]	11.80	1.08	3.54

Above table includes uncertainty factors of:

1.3 for all static heat loads

1.1 for all dynamic heat loads.

From: SLAC Engineering Note: LCLS-II Cryogenic Heat Load

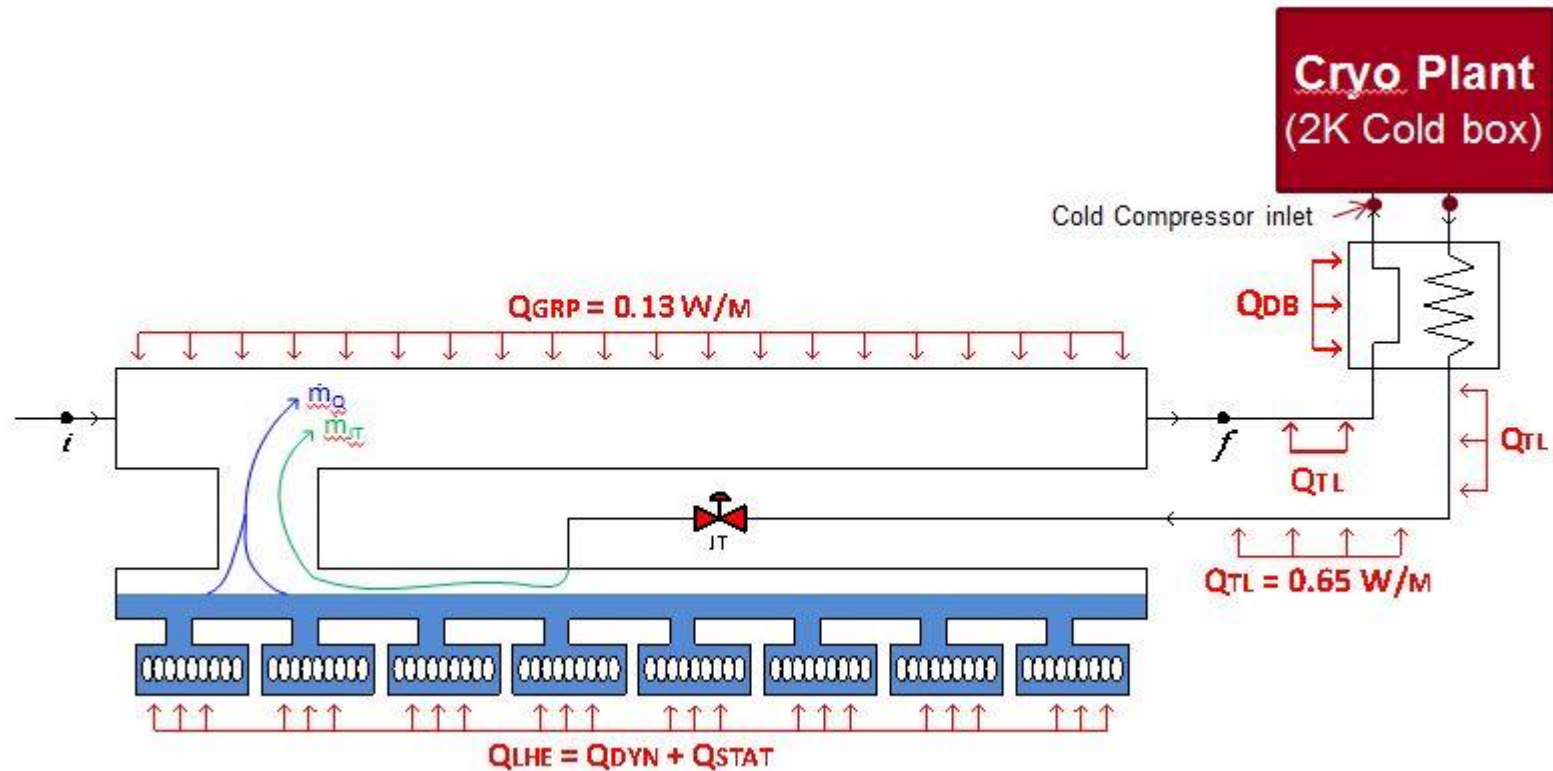
Note Number: LCLSII-4.5-EN-0179

Temperatures and Pressures for Cryogenic System Design

		High temprature shield	5 K to 8 K	2.0 K
		Temperature level	Temperature level	Temperature level
		(module)	(module)	(module)
Temperature out of distribution box	(K)	35.00	4.5	2.5
Pressure out of distribution box	(bar)	3.7	3.0	3.0
Enthalpy out	(J/g)	197.7	11.8	5.713
Entropy out	(J/gK)	17.7	3.6	1.913
Temperature return to distribution box	(K)	55.00	5.9	2.15
Pressure return to distribution box	(bar)	2.7	2.9	0.0294
Enthalpy return	(J/g)	302.0	30.9	25.95
Entropy return	(J/gK)	20.7	7.2	13.15

From LCLScryoHeat-30July2014-100percent.xlsx

Simplified Heat Load Diagram



System Pressure Drops

Pressure drops must be analyzed for each helium flow path to ensure that steady-state operation matches system design and that non-steady conditions (cool-down, emergency venting, warm-up) are properly handled

- Input variables include line size,
- Allowable temperature rise,
- Allowable pressure drop
- Heat load (temperature rise and heat load → mass flow)
- Maximum allowable pressure for emergency venting
- Matching cryomodule/distribution system to the cryogenic plant

Cryo-mechanical safety and code compliance

Pressure vessels, piping, ODH

- Helium vessel around the cavity is the pressure vessel
- Piping must all meet pressure piping standards
- Fermilab ES&H manual section 5000 includes cryogenic system safety, pressure vessel standards, SRF dressed cavity standard, vacuum vessel standard, oxygen deficiency hazards (ODH), etc.
- SLAC, Fermilab, and JLab will agree upon a common set of standards based on these and those at the partner labs
 - Baseline is to use FNAL safety requirements

Seismic analysis

- Fermilab is presently doing mechanical analyses of a cryomodule assembly under various acceleration and/or oscillatory modes as required by SLAC
- These are also needed for design for shipping

Additional necessary engineering documents

Fermilab-style safety engineering notes

- Dressed cavity helium vessels
 - Demonstrates compliance with pressure vessel rules
- Piping engineering note
 - Demonstrates compliance with pressure piping rules
- Vacuum vessel engineering note
 - Demonstrates compliance with vacuum vessel rules

Piping mechanical loads and stability

- Static piping pressure loads, support structure stresses, and interconnect stability
- Dynamic analyses for shipping and seismic issues

Various other documents verifying design and interfaces

Most of these specific documents for LCLS-II cryomodule are not yet started

- But similar documents exist for our previous 1.3 GHz and 3.9 GHz cryomodules and will serve as drafts for these
- Strong similarities among piping, vessel, and structural features mean most work for these documents has been done

Cryomodule Design / Production Model

LCLS-II SRF linac closely based on European XFEL / ILC / TESLA design

- Under development ~ 20 years with > 1000 cavities to be made and tested (incl. 800 for E-XFEL – completed 2015)

FNAL has been working with these designs for ~10 years in ILC context

- Two cryomodules built and tested: CM1 and CM2
- 80 9-cell cavities procured
- >300 bare 9-cell cavity tests (vertical test)
- >30 dressed 9-cell cavity tests (horizontal test)

FNAL is responsible for the CM design, working closely with JLab & SLAC

FNAL and JLab produce two streams of identical 1.3 GHz CM, starting with two prototypes

- Tightly coordinated activity among partner labs
- Common procedures, test reporting, travelers, etc. (within infrastructure limits)
- Taking advantage of Jlab cryomodule production experience

FNAL produces two 3.9 GHz CM's

- Based on a four-cavity 3.9 GHz linearizer cryomodule built for DESY/FLASH

Cooperation and assistance from DESY/XFEL extremely beneficial

Conclusions for cryomodule design

Design effort and duration are minimized

- Deviations from previous TESLA-style cryomodules are necessary, but structure and form are very much the TESLA concept with minimal modifications
- Component design effort and technical risk minimized by using existing designs with minimal modification
- Using prototypes to advance and confirm design concepts early

Substantial Fermilab and partner lab experience and capabilities

- Emphasizing integrated system design

Rapid design progress

- LCLS-II inclusion of superconducting RF structures began just one year ago

Conclusion for cryogenic system heat loads

- Cryomodule design, cryogenic distribution, and cryogenic plant must be designed as one cryogenic system.
- Detailed analyses and a complete roll-up of heat loads for the cryomodules and cryogenic distribution have been completed.
- Associated supply and return helium conditions have been coordinated with Jlab cryogenic plant designers for a consistent system design.
- This presentation highlighted some aspects of the cryomodule and cryogenic distribution design and analyses including steady-state operational heat loads.

Acknowledgments

This presentation includes information from many people at Fermilab, Jlab, and SLAC involved in cryomodule design, cryogenic distribution design, and overall cryogenic system design.

Special thanks to John Galayda, Camille Ginsburg, Chuck Grimm, Joshua Kaluzny, Arkadiy Klebaner, Yuriy Orlov, and Marc Ross, who provided slides for this presentation.

Backup slides, additional information

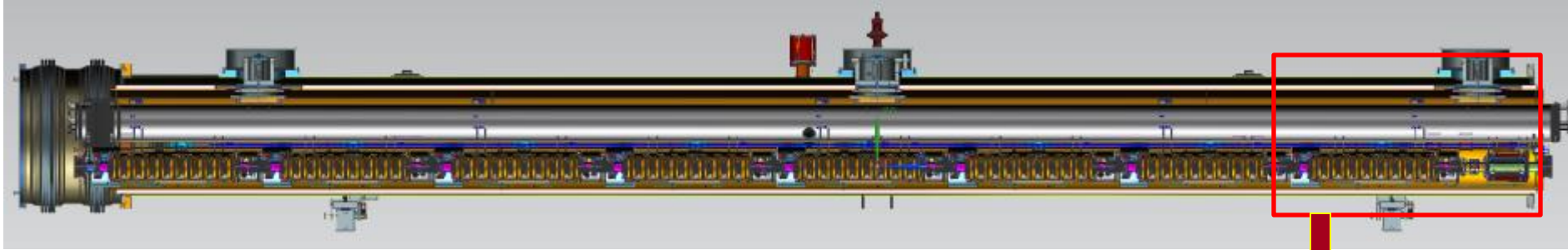
TESLA-style cryomodules compared - 1

Pipe function	BCD <u>name</u>	TTF inner diameter (mm)	XFEL inner diameter (mm)	Type IV (ILC) inner <u>dia</u> (mm)	LCLS-II inner diameter (mm)
2.2 K <u>subcooled</u> supply	A	45.2	45.2	60.2	45.0
Gas helium return header, structural support	B	300	300	300	300
5 K shield and intercept supply	C	54	54	56.1	55.1
8 K shield and intercept return	D	50	65	69.9	55.1
High temperature shield and intercept supply	E	54	65	72.0	55.1
High temperature shield and intercept return	F	50	65	79.4	52.5
2-phase pipe	G	72.1	>72.1	69.0	95.5
Helium vessel to 2-phase pipe nozzle (“chimney”)		54.9	54.9	54.9	95
Warm-up/cool-down line	H			38.9	38.9

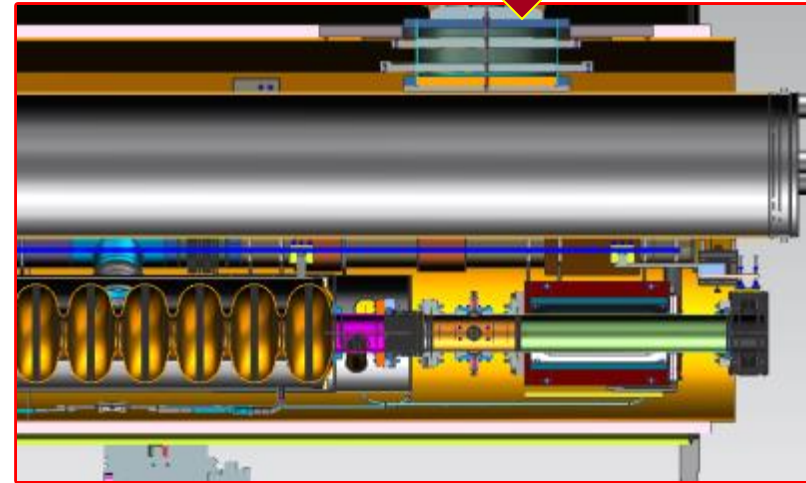
TESLA-style cryomodules compared - 2

Feature	TTF (type 3+)	XFEL	Type IV (ILC)	LCLS-II
Cavity cold slot length (mm)	1383.7	1383.7	1326.9	1383.7
Cryomodule slot length (mm)	12450	12220	12652	12220
Magnet style	Bath cooled at 4.5 K	Bath cooled at 2 K	Conductively cooled to 2 K	Conductively cooled to 2 K
Magnet location	End	End	Middle	End
Current leads	Vapor cooled from 4.5 K	Conductively cooled	Conductively cooled	Conductively cooled
BPM style				
5 K thermal shield	YES	YES	YES	NO, but retain intercepts
Input coupler	TTF3 design	TTF3 modified for better thermal intercepts		Modified TTF3 for CW cooling

1.3 GHz Cryomodule Layout, Magnet and BPM



- Vacuum Vessel & Bellows
- Coldmass supports
- Cold mass
 - HGR Pipe with bearings
 - Cavity string
 - ✓ Cavity with lever tuner
 - ✓ Splittable quad (conduction cooled)- V. Kashikhin
 - ✓ BPM (Reentrant or Button)
 - ✓ Gate valve
 - ✓ Invar rod



Cryomodule pipe pressures

Pipe function	BCD <u>name</u>	Nominal operating pressure (bar)	Design pressure (MAWP) (bar)
2.2 K <u>subcooled</u> supply	A	3.0	20.0
Gas helium return header, structural support	B	0.031	2.0 warm 4.0 cold
5 K shield and intercept supply	C	3.0	20.0
8 K shield and intercept return	D	2.9	20.0
High temperature shield and intercept supply	E	3.7	20.0
High temperature shield and intercept return	F	2.7	20.0
2-phase pipe	G	0.031	2.0 warm 4.0 cold
Helium vessel to 2-phase pipe nozzle (“chimney”)		0.031	2.0 warm 4.0 cold
Warm-up/cool-down line	H	0.031 - 1.5	2.0 warm 4.0 cold

Helium inventory

Location	Number of modules	State	Temperature (K)	Pressure (bar)	Pipe ID (mm)	Density (kg/m3)	Volume (liters)	Mass (kg)	Equiv liquid (4.2 K liters)
One helium vessel		liquid	2.00	0.031		145.700	23.00	3.35	26.8
8 helium vessels	1	liquid	2.00	0.031		145.700	184.00	26.81	214.5
2-phase pipe liquid	1	1/2 dia liquid	2.00	0.031	95.0	145.700	43.22	6.30	50.4
2-phase pipe vapor	1	1/2 dia vapor	2.00	0.031	95.0	1.008	43.22	0.04	0.3
300 mm pipe vapor	1	vapor	2.00	0.031	300.0	1.008	861.93	0.87	7.0
5 K supply	1	supercritical	5.00	5.000	56.1	129.000	30.14	3.89	31.1
8 K return	1	supercritical	8.00	4.000	69.9	30.760	46.79	1.44	11.5
30 K supply	1	gas	30.00	16.000	72.0	24.660	49.65	1.22	9.8
50 K return	1	gas	50.00	14.000	79.4	12.970	60.38	0.78	6.3
Warmup line	1	vapor	2.00	0.03	38.9	145.700	14.49	2.11	16.9
TOTALS									
One module	1						1333.81	43.46	347.7
LCLS-II module total	37						49351.07	1608.18	12865.4

Each dressed cavity – 27 liquid liters

8 dressed cavities – 214 liquid liters

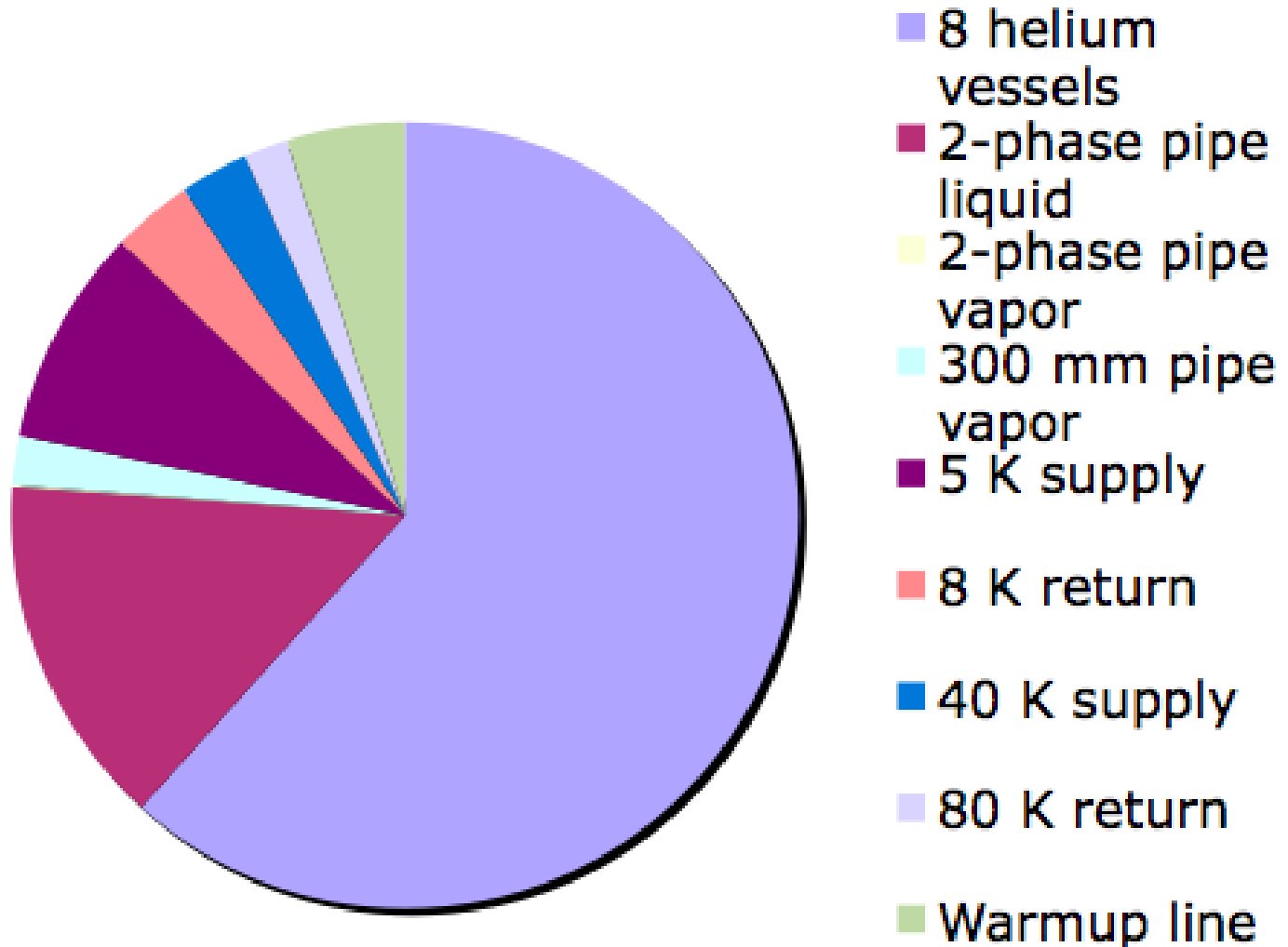
Pipes – 134 liquid liters equivalent mass

One cryomodule total – 348 liquid liters equivalent

LCLS-II cryomodules – 13,000 liquid liters equivalent

Helium mass in a cryomodule

(95 mm 2-phase pipe 1/2 full of liquid)



Recent Revisions for Heat Load Reduction

In order to reduce the cryogenic system heat load at 2 Kelvin to a total within the capacity of the planned Jlab cryogenic plant (4.0 kW at 2 K), the project made the following revisions to requirements:

- 100% of cavities are powered so that average gradient may be reduced (reduces assumed gradient from 16 MV/m to 15 MV/m and reduces dynamic heating by about 4.5 W per CM)
- Beam current is reduced from 0.3 mA to 0.1 mA (reduces HOM loads at 2 Kelvin to 1/3 of 0.3 mA value)
 - Additional reduction via copper coating of inter-cavity bellows
- Above two changes are the major ones and reduce estimated heat load for each cryomodule by about 10 Watts

Resulting total heat load at 2.0 K including uncertainty factors is 3.54 kW

CM Static Heat Load

Heat Load, [W]	High temperature thermal shield	Low temperature thermal intercepts	2.0 K Circuit
Cryomodule static	100	12	6

Basis of estimate:

- Carlo Pagani, 2nd ILC Acc. Workshop, 8/16/2005 (TTF measurements at DESY)
- X.L. Wang, et. al., TTC 2011 (CMTB measurements at DESY)
- B. Petersen et. al., XFEL predicted based on measurements and analyses
- N. Ohuchi, S1-G-report(Thermal Test).doc (S1-Global measurements at KEK)

Cryo Distribution System Static Heat Load Budget

Heat Load, [W]	High temperature thermal shield	Low temperature thermal intercepts	2.0 K Circuit
CDS	3,400	260	220

Basis of estimate:

- NML measurements at Fermilab
- Riddone, G. et. al., "Results from the Qualification of the Three Pre-Series Test Cells for the LHC Cryogenic Distribution Line"
- Gruehagen, et. al., "Long, Bellows-Free Vertical Helium Transfer Lines for the LHC Cryogenic System"
- Parente, C., et. al., "The Local Helium Compound Transfer Lines for the Large Hadron Collider Cryogenic System"
- FEA of the current design

Details → **LCLS-II Cryogenic Heat Load**, Note Number: LCLSII-4.5-EN-0179

2 K heat in first few cryomodules

Cryomodule	L0		L1		HL		L2		L3 CM16	
E for all cavities powered [MV/m]	14.00		15.00		11.72		15.00		15.00	
Baseline E with fraction of cavities powered (MV/m)	16.00		16.00		12.50		16.00		16.00	
Q	2.7E+10		2.7E+10		2.5E+09		2.7E+10		2.7E+10	
Number of cryomodules	1		2		2		12		1	
Number of cavities per CM	8		8		8		8		8	
Number of cavities total	8		16		16		96		8	
Baseline powered cavities total	7.0		15.0		15.0		90.0		7.5	
Baseline fraction of cavities powered	0.88		0.94		0.94		0.94		0.94	
Cavity length [m]	1.038		1.038		0.346		1.038		1.038	
R/Q [ohms]	1036		1036		750		1036		1036	
Baseline beam current [mA]	0.30		0.30		0.30		0.30		0.30	
New beam current for analysis [mA]	0.10		0.10		0.10		0.10		0.10	
Dynamic RF load per cavity [W]	7.55		8.67		8.77		8.67		8.67	
HOMs with baseline 0.3 mA current [W]	8		8		15		10		30	
HOMs with new current for analysis [W]	2.7		2.7		5.0		3.3		10.0	
Transient [W]	0		0		0		0		0	
Transient with new beam current for analysis [W]	0		0		0		0		0	
Portion of HOMs and Transient to 2K	0.20		0.20		0.20		0.20		0.20	
Remaining Portion of HOMs and Transient to 40K	0.80		0.80		0.80		0.80		0.80	
	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic	Static	Dynamic
Temperature Level	2K		2K		2K		2K		2K	
RF dynamic load		60.40		69.33		70.15		69.33		69.33
Magnet current leads	0.56	0.03	0.56	0.03	-	-	0.56	0.03	0.56	0.32
Electric heater		2.00		2.00		2.00		2.00		2.00
Other dynamic loads per CM		0.60		0.69		0.70		0.69		0.69
Input coupler	0.48	0.12	0.48	0.12	0.48	0.12	0.48	0.12	0.48	0.12
HOM coupler (cables)		0.18		0.18		0.18		0.18		0.18
HOM absorber (conduction to 2 K)		-		-		-		-		-
HOM to structure		0.53		0.53		1.00		0.67		2.00
Static, dynamic sum	6.00	63.87	6.00	72.89	6.00	74.15	6.00	73.03	6.00	74.65
Active CM 2K Sum [W]	69.9		78.9		80.1		79.0		80.7	

94%

From LCLScryoHeat-30July2014-100percent.xlsx

Heat loads and cryogenic plant size

Heat loads are carefully evaluated

- Input from various groups including beam dynamics, RF cavity performance, input couplers, cryomodule design, magnets and current leads, distribution system
- These are tabulated as “best estimates” meaning no margin added. These are the expected values

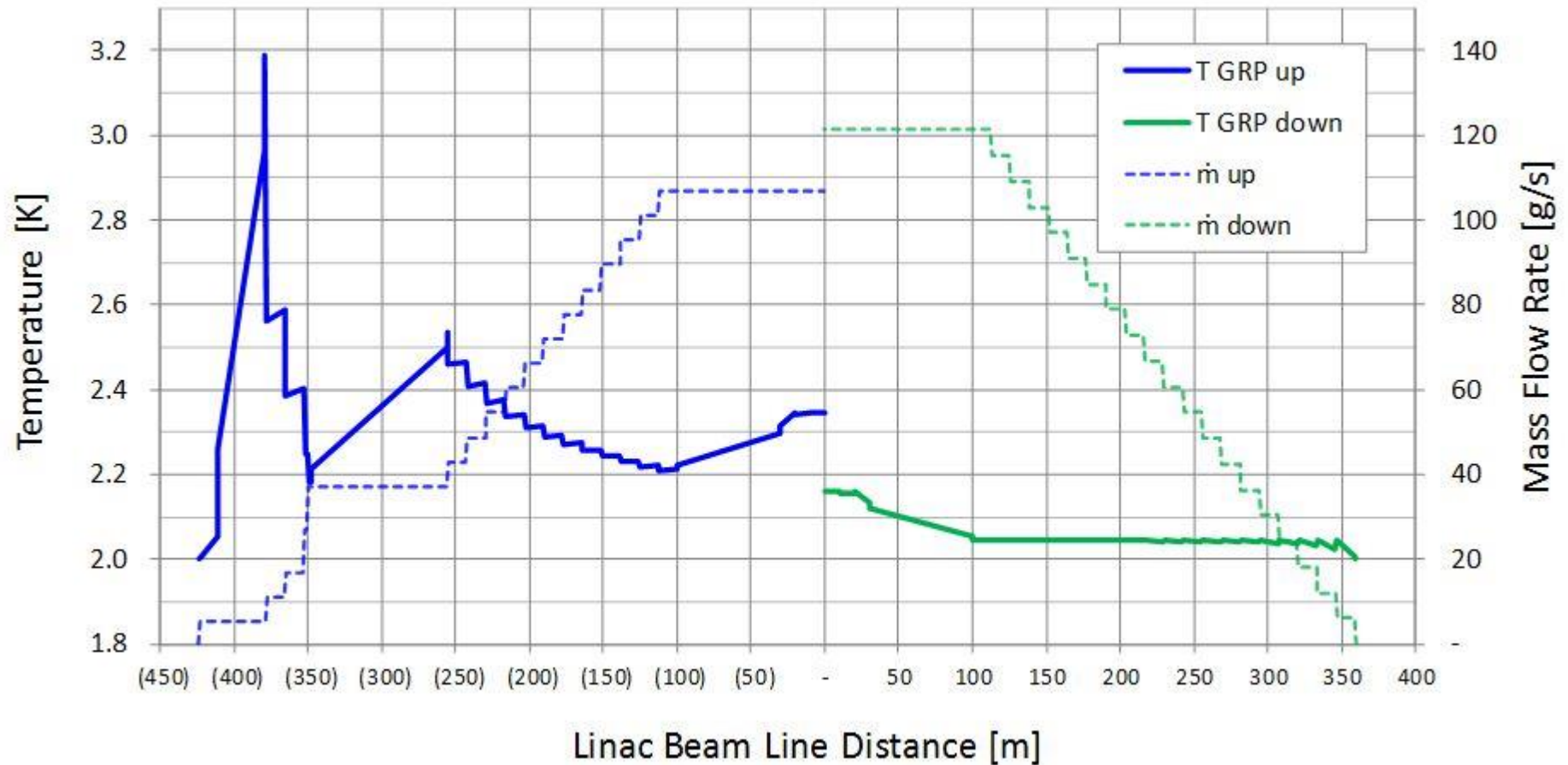
Then also an uncertainty factor must be applied

- Heat load x uncertainty factor = maximum anticipated
- Uncertainty factor evaluation should be quantitatively based on measurements and statistics

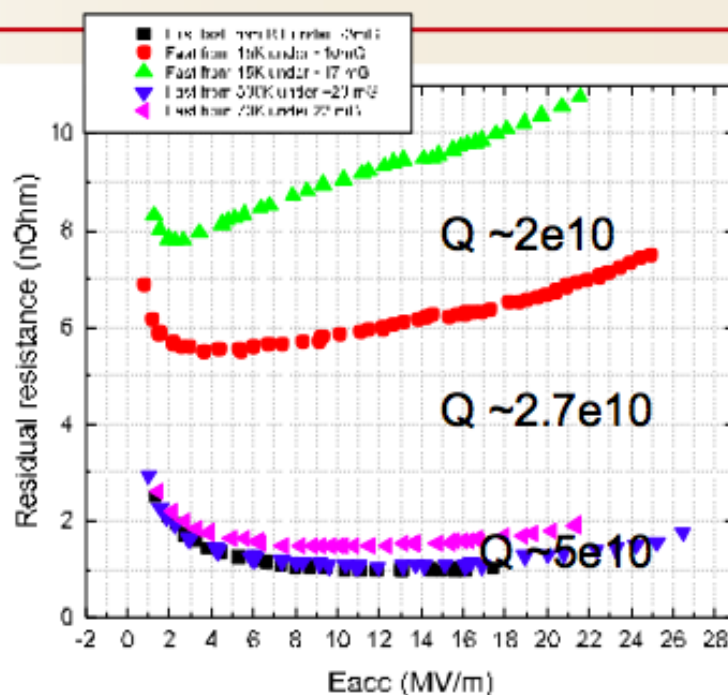
These then provide input to the cryogenic plant design and sizing

- Temperature and pressure constraints agreed upon by various cryogenic system designers provides additional input
- Combinations of heat loads (e.g., static only, static +RF, static + RF + beam) provide various “modes” for cryogenic plant operation

GRP Temperature Profile (illustrates some of our work)



A further breakthrough at FNAL: optimal cooling conditions can produce extra low residual resistance despite large ambient fields



New recent findings at FNAL: cooling conditions exist to do even better than previously shown:

- Optimal cooldowns in 25 mGauss ambient field produce about 1 nOhm residual resistance! -> this corresponds to a sensitivity of 0.04 nOhm/mG
- Recently verified even in 50 and 100 mGauss!
- In VTS: first knob is fast cooling. Second is starting T.

Our interpretation at FNAL of what ultimately matters

- We think the quantity that might matter to expel flux efficiently is dT/dx (spatial thermogradient) – the highest the better – to win the pinning force
- There has to be a path (clear SC-NC interface boundary) for flux to escape
- Fast rate and starting temperature are therefore knobs to turn to obtain the needed depinning force – interpretation already presented in *A. Romanenko et al J. Appl. Phys.* **115**, 184903 (2014)

“The second possibility is that thermal gradients present during fast cooldown may exert a depinning force on the vortices, which counteracts trapping and helps pushing the flux out of the superconductor. In Fig. 11, a temperature difference between the lower iris and equator of a fine grain 1-cell EP cavity is shown as a function of the equator temperature, which shows that temperature differences of the order of 1–2 K are present during the fast cooling. This translates into local temperature gradients of $<\sim 0.4$ K/cm, which may be high enough for fluxoid depinning around T_c leading to the more efficient flux expulsion in the case of fast cooling. During a very slow cool-down temperature gradients are unavoidably very small, no thermal depinning force is aiding the expulsion, and the efficiency of flux expulsion may decrease.”

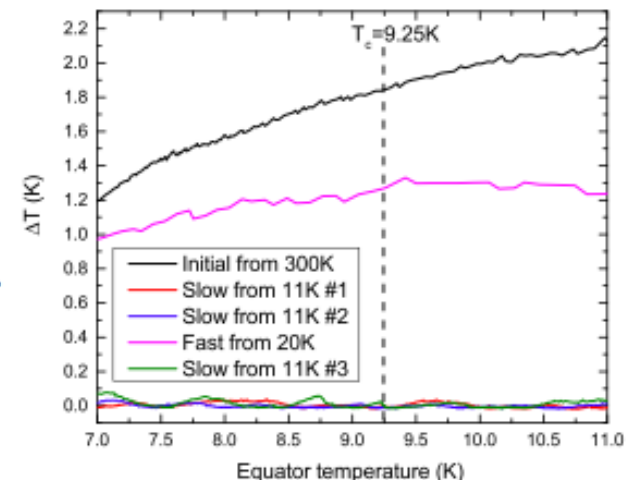


FIG. 11. Temperature difference between the equator and lower iris of the 1-cell cavity during different cooling procedures.

Cool-down requirements

We must cool slowly through from 300 K until most thermal contraction is complete. Cool-down rates (dT/dy and dT/dt) based on DESY measurements and analysis, in order to limit stresses on the support posts, must be limited in the Gas Return Pipe (GRP)

- GRP vertical gradient is < 15 K
- GRP longitudinal gradient is < 50 K
- GRP cool-down rate is 40 K/hr

May start fast cool-down at 80 K or colder

- “Fast” means 2 – 3 K/minute (“slow” < 0.5 K/minute)
- Since thermal shield is ~ 35 K – 55 K, in the following analysis use 40 K delta-T at 3 K/minute = 13 minutes for transition from thermal shield temperature to below the niobium 9.2 K critical temperature

LCLS-II Cryomodule Volumes

Location	Number of modules	State	Temperature (K)	Pressure (bar)	Pipe ID (mm)	Density (kg/m3)	Volume (liters)	Mass (kg)	Equiv liquid (4.2 K liters)
One helium vessel		liquid	2.00	0.031		145.700	23.00	3.35	26.8
8 helium vessels	1	liquid	2.00	0.031		145.700	184.00	26.81	214.5
2-phase pipe liquid	1	1/2 dia liquid	2.00	0.031	95.0	145.700	43.22	6.30	50.4
2-phase pipe vapor	1	1/2 dia vapor	2.00	0.031	95.0	1.008	43.22	0.04	0.3
300 mm pipe vapor	1	vapor	2.00	0.031	300.0	1.008	861.93	0.87	7.0
5 K supply	1	supercritical	5.00	5.000	56.1	129.000	30.14	3.89	31.1
8 K return	1	supercritical	8.00	4.000	69.9	30.760	46.79	1.44	11.5
30 K supply	1	gas	30.00	16.000	72.0	24.660	49.65	1.22	9.8
50 K return	1	gas	50.00	14.000	79.4	12.970	60.38	0.78	6.3
Warmup line	1	vapor	2.00	0.03	38.9	145.700	14.49	2.11	16.9
TOTALS									
One module	1						1333.81	43.46	347.7
LCLS-II module total	37						49351.07	1608.18	12865.4

- Fast cool-down of one cryomodule implies replacing 200 liters of helium volume as quickly as possible.
- From the previous slide, we want to replace those 200 liters, starting at 40 K, with helium at ~ 5 K in 13 minutes.
- Flow into the cryomodule at 15 liters/minute = 31 grams/sec liquid helium in liquefier mode. (~2 liters/min for each helium vessel)
- 31 g/s sets cool-down valve size

Cryogenic plant capacity

(Cryo Plant Performance Sheet from Dana Arenius, August 5, 2014)

Mode 3, Max. Liquefaction capacity of the plant at 4.5K.

Load Description	<i>w</i> [g/s]	<i>Supply</i>		<i>Return</i>		<i>q</i> [kW]	<i>E_L</i> [kW]	<i>Frac E_L</i> [-]
		<i>p</i> [atm]	<i>T</i> [K]	<i>p</i> [atm]	<i>T</i> [K]			
W. Shield	168.2	3.7	44.0	2.70	56.50	11.00	88.1	10%
C. Shield	25.6	3.2	5.8	1.06	311.80	1.1	56.2	19.0
4K Liquefaction	136.0	3.2	4.5	1.10	300.0		923.5	86%
Cold Compressor								
Total Load Exergy							1068 kW	

In liquefier mode (supplying 4.5 K, receiving back warm helium gas), 31 grams/sec is no problem.

- However, 4 cryomodules would require $4 \times 31 = 124$ gr/sec, about the limit of cryogenic plant production
- L3 has 20 cryomodules cooled in parallel
 - 31 grams/sec per cryomodule would not be available
- Need to focus cooling on a few cryomodules

Conclusion for cool-down concept

Required cool-down rate is feasible

- “Fast” cool-down is not impossibly fast in a cryomodule
- Cryogenic plant can provide the flow for a few cryomodules at a time
- Capillary tubes and other pipes can carry the flow
- Note that line H (cool-down / warm-up line) exists only in the cryomodules and is eliminated from the distribution system.

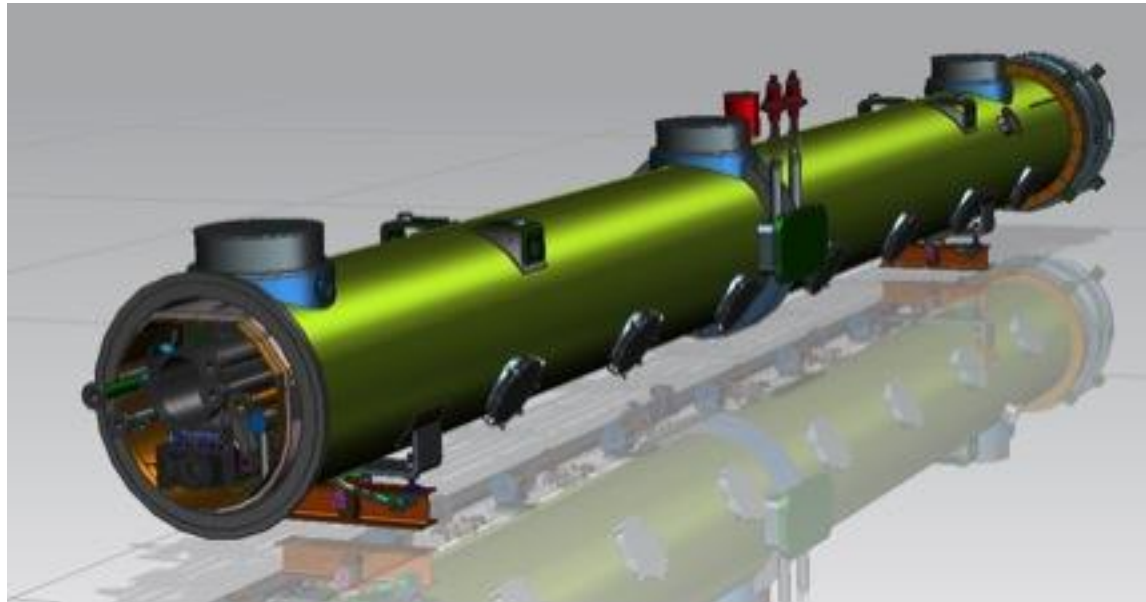
Implementation . . .

- Isolate Line H (cool-down / warm-up line) for each cryomodule and provide each cryomodule with its own cool-down valve, supplied from Line A (helium supply) as shown in slide 7 and in 3-D model images

Tuner access ports

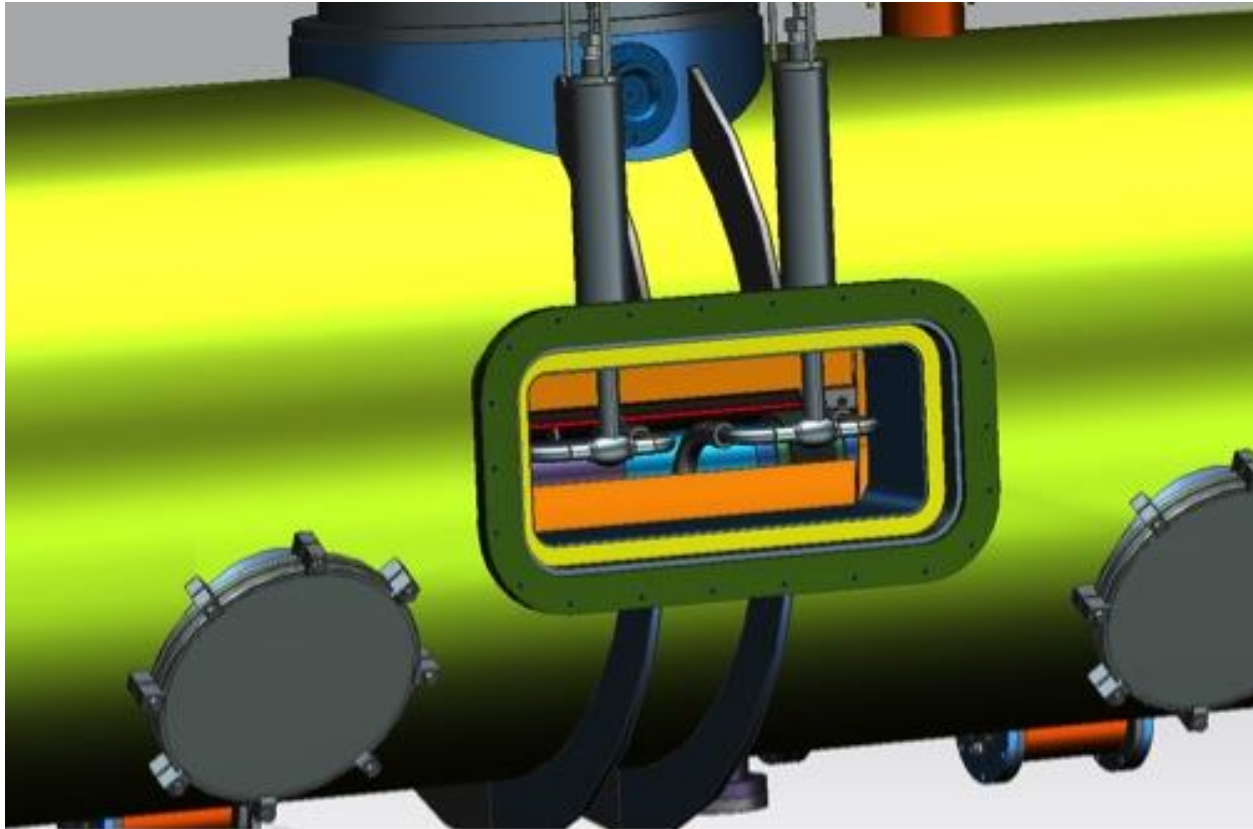
- Cornell ERL injector cryomodule successfully incorporated access ports
- Allow access to tuner motor, drive mechanism, and piezos without pulling the cavity string out of cryostat.
 - Fermilab tuner designed to allow access to critical components via access ports
 - Ports must be on opposite side from input couplers, which is the wall side in the SLAC tunnel
 - Ports available during initial CMTS tests
 - Ports would not enable access to XFEL end-lever tuner
- Definitely include access in prototype cryomodules
 - These will incorporate Fermilab tuner
 - Mitigates risk of problems with new tuner design
- Include access ports in production cryomodule?
 - Decision based on cost / risk analysis following initial tuner tests in HTS.
 - Assemble a mechanical mock-up including thermal shield and MLI to check access port utility.

1.3 GHz Prototype Cryomodule. Back View



- Tuner motor access ports
- JT Valve and cool-down valve with access port

1.3 GHz CM. Tuner & JT Valve access Ports



- Tuner port, Flange type ISO, ID=12"
- Valve Weld Access Port for final orbital welding for connection to JT Valve and Cool-down Valve

Draft instrumentation list – prototype cryomodule

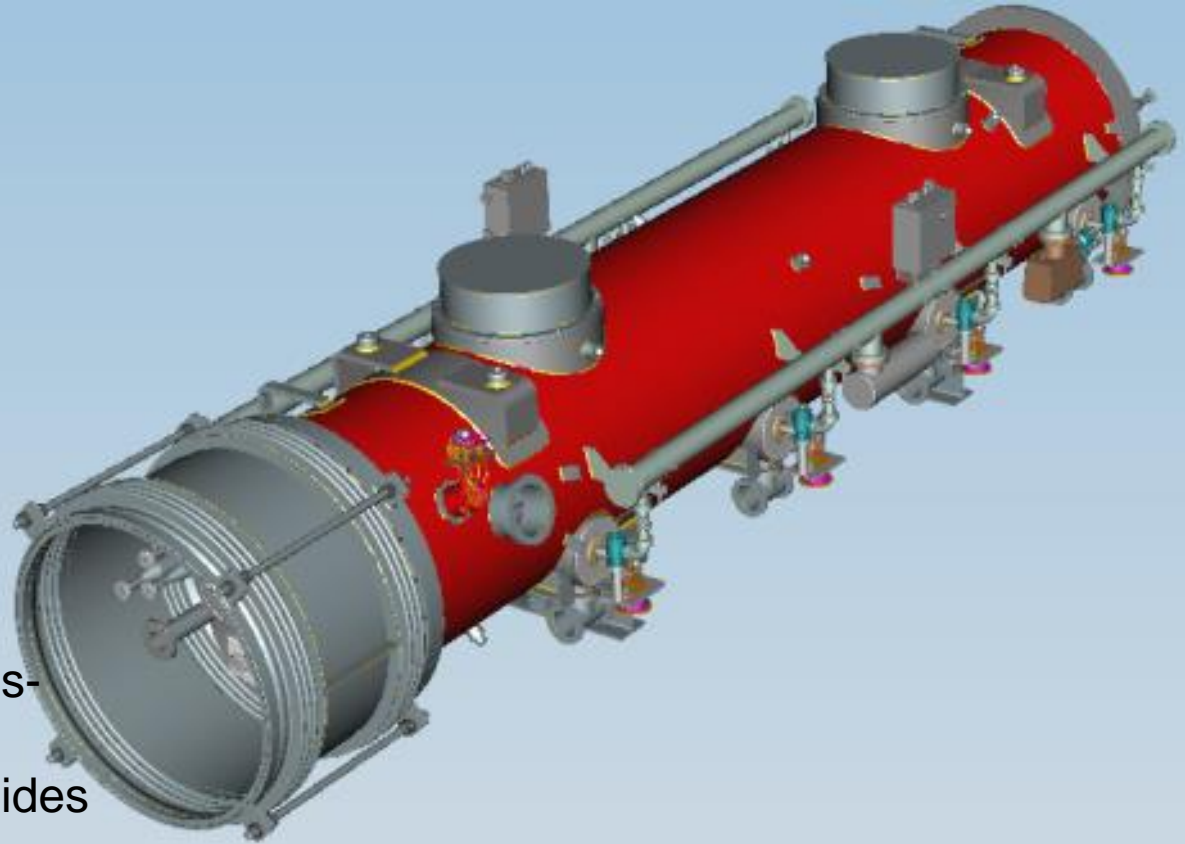
Device	Number of Devices per CryoModule
Piezo Actuator (Wiring)	32
Stepper Motors and Imbedded Platinum Sensor (Wiring)	8
Cavity RF Field Probes (Transmitted Power)	8
HOM RF Field Probes (Transmitted Power)	16
Coupler Electron Pick-Ups (eCY, eWG)	16
Beam Loss Monitor Wiring (Ionization Chamber)	3
Beam Loss Monitor Wiring (Diamond Beam Loss Monitor)	1
Helium Vessel Cernox RTDs & Wiring	8
HOM Cernox RTDs & Wiring	32
Coupler Interlock Platinum RTDs & Wiring	16
300mm Pipe Cool Down Cernox RTDs & Wiring	6
5K & 35K Shield Cernox RTDs & Wiring	4
Beam Loss Monitor (Ionization Chamber) Cernox RTDs & Wiring	3
2 Dipole Corrector Package Voltage Taps, Heaters, Cernox RTDs, & RTD Wiring	1
Quad Magnet Voltage Taps, Heater, Cernox RTDs, & RTD Wiring	1
Helium Vessel Cartridge Heater & Wiring	8
Magnetic Sensors (Outside of Cavity Helium Vessel)	1
Helium Liquid Level Probes & Wiring	2

Instrumentation notes

List is being updated with some changes

- Replacing most CERNOX sensors with diodes for cost savings
- Reviewing other needs
 - Beam loss monitors
 - Helium vessel heater design
- Production cryomodule instrumentation will be a reduced set

XFEL, 3.9 GHz Cryomodule



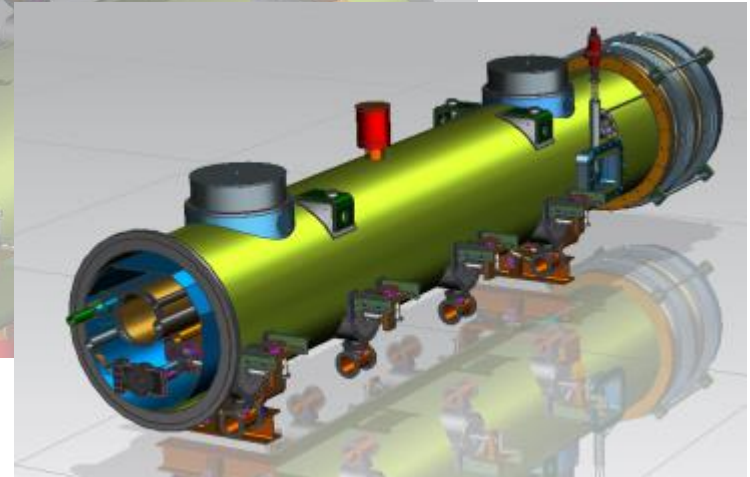
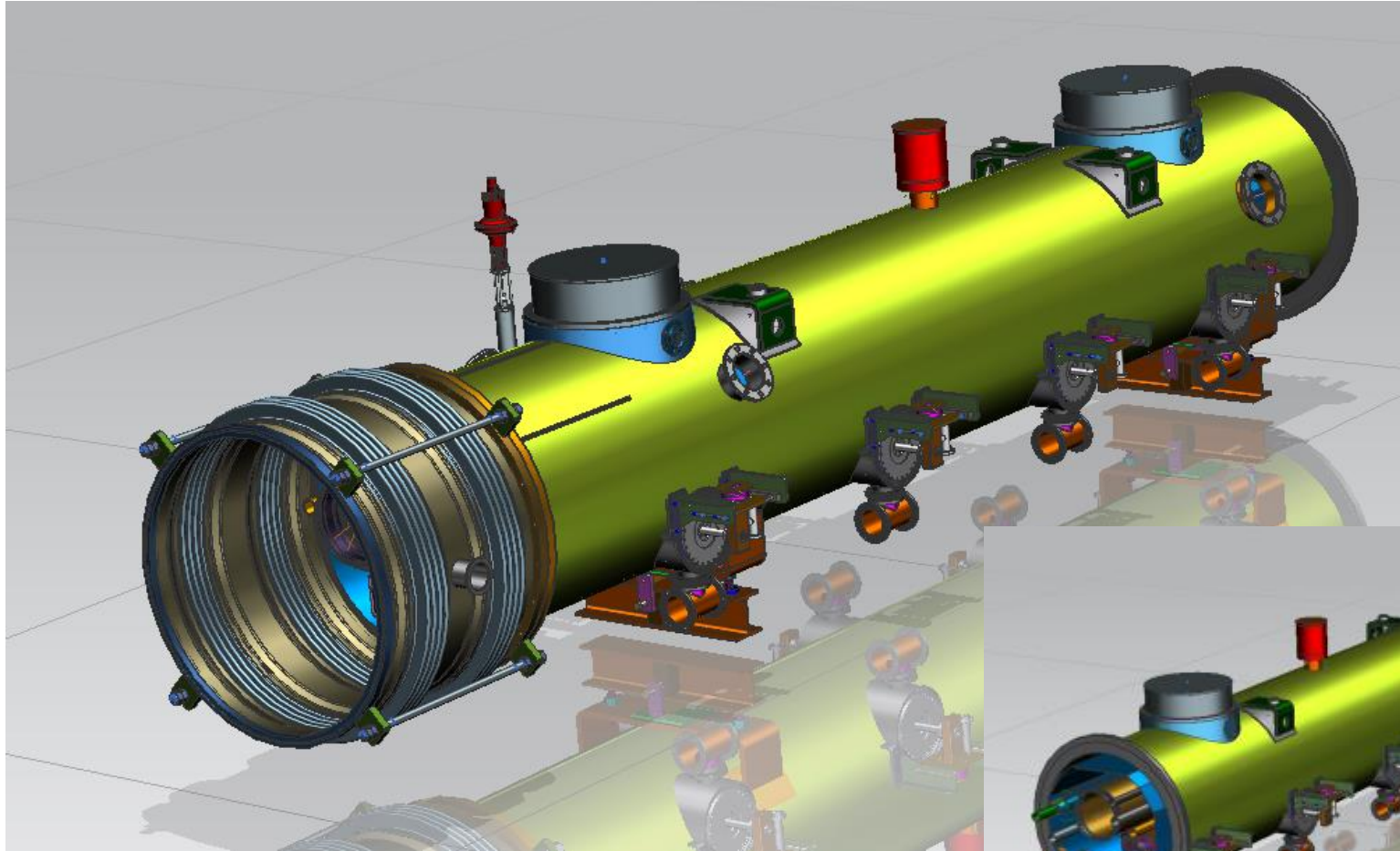
- 8-3.9GHz Cavities (4 cavities-3.8GHz-FNAL)
- Power couplers from both sides
- 2-coldmass supports
- Interconnection Bellows (not sliding)
- 38" OD vacuum vessel pipe

3.9 GHz CM DESY/FLASH experience

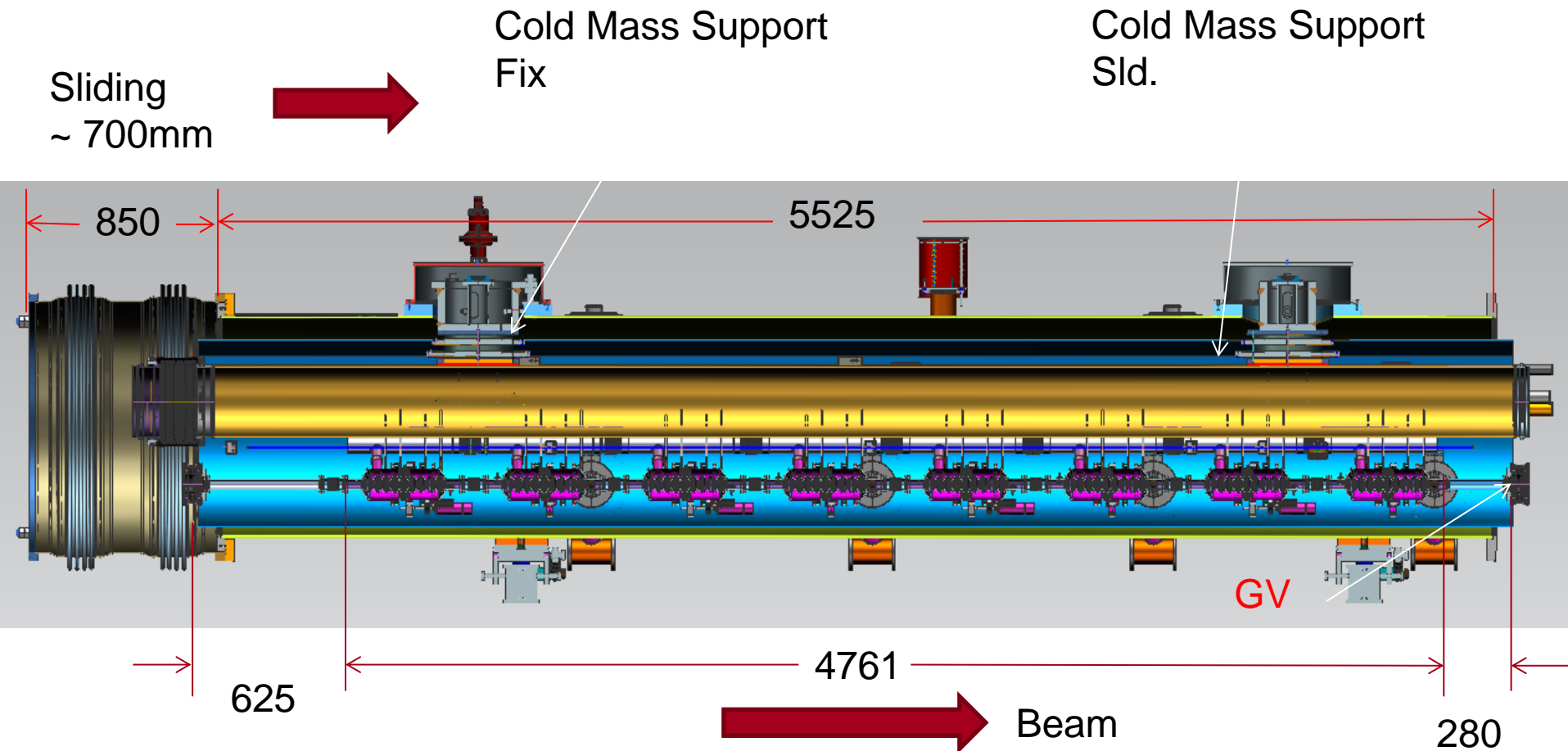
- 4-cavity 3.9 GHz pulsed-operation linearizer cryomodule designed and built at FNAL, installed at DESY/FLASH
 - Cavities routinely operate (pulsed) at 18.9 to 19.7 MV/m
- Cavities tested at FNAL both bare (vertical) and dressed (horizontal)
- Cryomodule first tested at DESY CMTB prior to installation in FLASH
 - Successful assembly
 - Successful transatlantic shipment
 - Some rework at DESY
 - Longitudinal realignment
 - Instrumentation terminations
- Inter-lab effort and coordination
 - Engineering Notes
 - Welding certification, esp. He vessels
 - Operational Readiness Clearance
 - Transatlantic CM transport



LCLS-II 3.9GHz Cryomodule, (F10014857 in Team Center)



3.9 GHz Cryomodule. Layout



- 8- 3.9GHz cavities
- MC distance 607.9 mm (COLD)